Naval Surface Warfare Center
Carderock Division
West Bethesda, MD 20817-5700

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Survivability, Structures, and Materials Directorate

Technical Report

Reliability-Based Operational Performance Metrics for Ship Structures

by

Paul E. Hess, III

DEPARTMENT OF THE NAVY

NAVAL SURFACE WARFARE CENTER, CARDEROCK DIVISION
9500 MACARTHUR BOULEVARD
WEST BETHESDA MD 20817-5700

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1. Enclosure (1) identifies and demonstrates, reliability-based operational performance metrics as they apply to surface ship structures, specifically, those of the US Navy. A method is presented for developing three performance metrics: structural operational capability, structural operational dependability and structural operational durability. Special emphasis is placed on defining the failure modes and definitions. Case studies are based on a notional US Navy ship design and include topside composite structures under a dynamic lateral pressure, unstiffened plate deformation due to wave slap, hull girder collapse in an extreme seaway and the initiation of a fatigue crack in a critical structural detail on the strength deck.

2. Comments or questions may be referred to Dr. Paul E. Hess, Code 654; telephone (301) 227-4118; e-mail, HessPE@nswccd.navy.mil.

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14. ABSTRACT

Program management is a discipline on which new systems and technologies are formed. It is very often concerned with reducing or mitigating the risks associated with cost, schedule and performance. This report introduces reliability-based performance metrics to manage structural system performance, specifically for Navy surface ships, and allows the risk associated with the platform structural performance to be mitigated as is done with other platform systems, such as electrical and mechanical systems. Ship acquisition and life-cycle management would be significantly improved, as it would allow the platform stakeholders a selection of figures of merit, upon which decisions can be based, and an accounting system for tracking the structure through its operational life. Current US Navy acquisition strategies do not incorporate quantitative structural performance measures and thereby do not adequately mitigate the programmatic risk of not meeting performance top-level requirements. The methodologies presented and demonstrated in this report serve as a starting point for achieving a completely quantitative, performance-based structural management environment based on existing structural analysis and reliability technologies.

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Notation

Acronyms

AASHTO	American Association of State Highways and Transportation Officials
ABS	American Bureau of Shipping
AISC	American Institute of Steel Construction
ALPS/ISUM	hull girder ultimate strength prediction computer code (Paik, 1993)
ANOVA	Analysis of Variance
AP	Aft Perpendicular
API	American Petroleum Institute
ASM	Advanced Second Moment
CLT	Classical Lamination Theory
COV	Coefficient of Variation
CRM	Continuous Risk Management
DD-21	next generation, US Navy destroyer
DOD	Department of Defense
DOE	Department of Energy
FAA	Federal Aviation Administration
FM	Failure Mode
FOM	Figure of Merit
FORM	First Order Reliability Method
FP	Forward Perpendicular
FRP	Fiber-Reinforced Plastic
FWD	forward
HSLA	High Strength Low Alloy steel
HTS	High Tensile Steel
HY-100	High Yield steel with a nominal yield strength of 100 ksi.
HY-80	High Yield steel with a nominal yield strength of 80 ksi.
ISSC	International Ship and Offshore Structures Congress
ksi	1000 pounds per square inch
LBP	Length Between Perpendiculars
LRFD	Load and Resistance Factor Design
LTONS	long tons = 2240 pounds.
MLFP	Most Likely Failure Point
MIL-HDBK	Military Handbook
MS	Mild Steel
msi	10^6 psi
MTBF	Mean Time Between Failures
MTTF	Mean Time To Failure
MTTR	Mean Time To Repair
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization

NORSOK	Norwegian Technology Standards Institution
NRC	Nuclear Regulatory Commission
NSWCCD	Naval Surface Warfare Center Carderock Division
NVIC	Navigation and Vessel Inspection Circular
OPNAVINST	Department of the Navy, Office of the Chief of Naval Operations Instruction
OS	Ordinary Steel
PDF	Probability Density Function
psi	pounds per square inch
RAO	Response Amplitude Operator
SE	System Effectiveness
SHCP	Ship Hull Characteristics Program (Rosborough 2001)
SLS	Serviceability Limit State
SPECTRA	computer code for seaway load prediction (Sikora 1998b)
SSC	Ship Structure Committee
SSD	Ship Structural Design (Hughes 1988)
TLR	Top-Level Requirement
ULS	Ultimate Limit State
ULTSTR	hull girder ultimate strength prediction computer code (Adamchak 1982)
US	United States
USN	United States Navy
VARTM	Vacuum-Assisted Resin Transfer Molding

Symbols

σ_X^N	equivalent normal standard deviation of X
α	aspect ratio, where α is the plate length divided by the plate width, or more simply: $\alpha = a/b$
ε	new evidence used for updating existing knowledge
ϕ	curvature of hull girder
γ	density of seawater
α	failure level
λ	parameter of exponential distribution, also called the failure rate
ν	poisson ratio
β	safety index where $p_f = 1 - \Phi(\beta)$
ϕ	strength factor of ultimate bending capacity
δ	structural response
ϕ	structure function
π	the constant pi is equal to approximately 3.14159
$\Phi(\,)$	standard normal cumulative probability function
μ_0	mean of prior distribution
σ_0	standard deviation of prior distribution
μ_1	mean of likelihood distribution
σ_1	standard deviation of likelihood distribution
$\Phi^{-1}(\,)$	inverse standard normal cumulative probability function
γ_D	load factor for dynamic bending moment
δ_f	structural response failure threshold
γ_i	load factor for i^{th} load
α_i*	directional cosine of limit state surface in reduced standard normal distribution space
ν_{ij}	poisson ratio in plane in *ij* direction
μ_L	mean value of load or load effect
σ_L	standard deviation of load or load effect
δ_l	structural response onset of failure or lower threshold of partial failure region
α_M	knockdown factor to account for moisture effects
μ_P	mean of posterior distribution
σ_P	standard deviation of posterior distribution
ΔQ_0	variable in Equation 6-10 (Hughes 1988) for predicting permanent set due to lateral pressure
ΔQ_1	variable in Equation 6-10 (Hughes 1988) for predicting permanent set due to lateral pressure
μ_R	mean value of resistance or strength
σ_R	standard deviation of resistance or strength
α_S	knockdown factor used to account for statistical uncertainty
γ_{SW}	stillwater bending moment partial safety factor
α_T	knockdown factor to account for temperature effects
δ_u	structural response at complete failure or upper threshold of partial failure region

γ_W	load factor for wave-induced bending load
γ_{WD}	load factor for combined wave-induced and dynamic bending
ϑ	random variable
μ_X^N	equivalent normal mean value of X
μ_Z	mean value of performance function Z, where $Z = R - L$
σ_Z	standard deviation of performance function Z, where $Z = R - L$
A	cross sectional area
A	failure level scale
A	N-axis intercept defining the S/N curve
a	plate length
Ao	Operational Availability
Ao'	Operational Durability of structural system
B	plate slenderness ratio
b	plate width
b	slope of S/N curve in Log-Log space
b_D	difference bias
B_L	Bias in load prediction
B_R	Bias in resistance of strength prediction
b_R	ratio bias
$B^R_{Real/Rules}$	bias between real strength and simple strength prediction model
B_D	modeling bias and uncertainty (real/predicted) for maximum lifetime dynamic wave bending load prediction, M_D
B_{SW}	modeling bias and uncertainty (real/predicted) for stillwater bending moment nominal prediction, M_{SW}
B_u	modeling bias and uncertainty (real/predicted) for ultimate bending capacity of ship hull girder prediction, M_u
B_W	modeling bias and uncertainty (real/predicted) for maximum lifetime wave-only, bending load prediction, M_W
B_{WD}	modeling bias and uncertainty (real/predicted) for maximum lifetime bending load prediction, M_{WD}
C	constant used in US Navy unstiffened plate deformation formulation that is defined by location of the plate and the plate material
c	distance from the neutral axis to the extreme fiber for beam bending
c	knockdown factor
c	nominal buckling knockdown factor
Co	Operational Capability
Co'	Operational Capability of structural system
Do	Operational Dependability or Mission Reliability
Do'	Operational Dependability or Mission Reliability of structural system
E	Elastic Modulus, also known as Young's Modulus
E_{ij}	elastic modulus in the ij direction, where i equals j
f_a	stress in plate due to lateral pressure
F_{CR}	critical buckling strength
F_{ij}	strength in the ij direction, where the strength is normal to the plane defined by coordinates i,j, if $i = j$, and where the strength is in shear if i does not equal j

f_{ij}	stress in the *ij* direction, where the stress is normal to the plane defined by coordinates *i,j*, if $i = j$, and where the stress is in shear if *i* does not equal *j*.
F_U	ultimate strength of material
$F_X(x)$	cumulative density function
$f_X(x)$	probability density function of random variable X
F_Y	nominal yield strength of steel
F_Y	yield strength
F_Y	yield strength of material
g	limit state function
g_{HG1}	first hull girder collapse performance function
g_{HG2}	second hull girder collapse performance function
G_{ij}	elastic modulus in shear in the *ij* plane
H	design head of water, or height of water column assumed to be acting on plate
i	general index
I	moment of inertia about the neutral axis
I_{NA}	moment of inertia about the neutral axis
K	shape factor determined by aspect ratio
k_D	dynamic bending moment probabilistic combination load factor
k_W	wave-induced bending moment probabilistic combination load factor
k_{WD}	probabilistic combination load factor for combined wave-induced and whipping
L	column length
$\underline{L}^*$	load vector coordinates for design point
L_i	i^{th} demand, load or load effect
M	bending moment
M_D	dynamic bending moment
M_{SW}	stillwater bending moment
M_u	ultimate bending capacity or resistance of ship hull girder
M_W	wave-induced bending moment
M_{WD}	combined wave-induced plus whipping, hull girder bending moment prediction, where $M_{WD} = M_W + k_D M_D$
M_Y	bending moment at which material yield occurs in extreme fiber of beam
N	number of cycles to failure for a specimen subjected to stress range S
$\hat{N}$	predicted number of cycles to failure for a specimen subjected to stress range S
n	total number of items
P	lateral pressure
p_f	probability of failure
Pr(A)	probability of the occurrence of event A
Pr(A|E)	probability of the occurrence of even A conditioned on the occurrence of the evidence E
Q	variable in Equation 6-10 (Hughes 1988) for predicting permanent set due to lateral pressure
Q_Y	variable in Equation 6-10 (Hughes 1988) for predicting permanent set due to lateral pressure
R	structural resistance or strength
R^*	strength coordinate for design point
$R_{AdvPred}$	strength predicted using advanced model

$R_{Experimental}$	experimental strength
R_{Real}	actual strength
R_{Rules}	strength predicted using simple model
Rw	variable in Equation 6-10 (Hughes 1988) for predicting permanent set due to lateral pressure
S	stress range for fatigue life prediction
S_e	standard error
$T()$	function in Equation 6-10 (Hughes 1988) for predicting permanent set due to lateral pressure
$Trunc$	location parameter for maximum lifetime load distribution output by SPECTRA
U	universe of all possible outcomes
w_p	permanent set of plate, or maximum out-of-plane deformation of heart of plate
$\underline{X}$	vector of random variables X_i
x^*	design point of random variable X
X_i	i^{th} random variable
x_i	value or instance of i^{th} random variable
x_i^*	design point of i^{th} random variable X
x_{Li}	i^{th} basic load variable
x_{Ri}	i^{th} basic strength variable
y_{deck}	distance from the neutral axis to the extreme fiber of the strength deck
y_{keel}	distance from the neutral axis to extreme fiber of the keel
Z	performance function
Z	section modulus about the neutral axis

Administrative Information

This dissertation was submitted to the faculty of the Graduate School of the University of Maryland in partial fulfillment of the requirements for the degree of Doctor of Philosophy, 2002. The dissertation was directed by Professor Bilal M. Ayyub, Ph.D., P.E., Professor of Civil and Environmental Engineering and Dr. Jeffrey E. Beach, Head, Structures and Composites Department, Naval Surface Warfare Center, Carderock Division.

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CHAPTER 1 INTRODUCTION

1.1 BACKGROUND

Program management is concerned with reducing or *mitigating* the risks associated with meeting cost, schedule and performance program goals. While the cost and schedule of a ship structural design and life-cycle management are of great interest to the ship owners and operators, the operational performance of a surface ship structure is traditionally assured using non-performance-based design criteria. Traditional design criteria imply an acceptable level of performance and safety through the use of embedded factors of safety and empirical coefficients which have evolved over time. The actual performance and safety levels are unknown, as they were and are still not explicitly considered in the ship structural acceptability criteria for the US Navy.

Traditional criteria were developed with the assumption of consistent ship structural configurations and unchanging performance and mission expectations. Changes to this relationship have come in the form of longer expected hull lives and non-traditional hull forms, meant to improve the nonstructural performance of the ship in the combat environment. Due to the evolutionary and implicit nature of the traditional design criteria, significant changes to the structural configuration cannot be accommodated without unknown, and possibly unfavorable ramifications to operational performance.

In order to effectively mitigate the risk resulting from these changes, the operational performance of the ship structural design must be assessed using explicit operational performance prediction methodologies, of which none currently exist. The measured performance must be compared to top-level performance requirements developed by the ship and program managers in order to determine acceptability of the ship structural design. Operational performance is the performance of the undamaged system during platform operation versus the performance during repair or construction, or after some damage has been incurred.

Structural reliability theory is typically used for the prediction of quantitative assessments of safety and risk of structural failure. This report introduces reliability-based performance metrics to manage structural system operational performance, specifically for Navy surface ships, and allows the risk associated with the platform structural performance to be mitigated as done with other platform systems, such as electrical and mechanical systems. The development of a quantitative, performance-based approach to design can be based on modifications to existing structural reliability theory.

Effective use of the performance metrics allows formal, quantitative consideration of the safety requirements of the platform structure, but in the context of performance. Risk is discussed here as a programmatic consideration versus that of safety, and is a primary concern of the owner/operators (for example, the US Navy).

Structural reliability theory has been implemented in design codes - mainly as a means of assuring some level of safety. While much research has gone into the development of reliability-based design criteria, actual implementation has been limited due to the question of what is acceptable risk. To achieve levels of risk consistent with past practice, the American Institute of Steel Construction (AISC) calibrated the new Load and Resistance Factor Design (LRFD) manual (AISC 1993) with designs produced by the existing working stress code. For vehicle design, such a risk-based approach does not allow improvements in performance, or changes in

the performance expectations as it is primarily concerned with assuring safety. The development of a more formal performance-based approach to design can be based on modified structural reliability theory. Top-level requirements (TLRs) based on a quantitative measure of performance allow the owner/operator to better articulate their needs to the design community. The missing ingredient is the methodology needed to determine if the TLRs have been met.

1.2 OBJECTIVE

The objective of this report is to build and demonstrate a methodology for the use of reliability-based, structural analysis technologies to support meeting top-level, operational performance requirements for naval surface ship structure during the design phase. Operational performance is the performance of the undamaged system during platform operation versus the performance during repair or construction, or after some damage has been incurred. Such a methodology will support the mitigation of programmatic risks in acquisition management of a ship structural system design. The proposed metrics and supporting methodologies are intended to use existing technologies or extensions to current technologies. Special emphasis is placed on defining the failure modes and definitions for use in a reliability-based, operational performance analysis. The case studies are based on a notional ship design and include topside composite structures under a dynamic lateral pressure, unstiffened plate deformation due to wave slap, hull girder collapse in an extreme seaway and the initiation of a fatigue crack in a critical structural detail on the strength deck.

The methodologies presented and demonstrated in this report serve as a starting point to achieving a completely quantitative, operational performance-based structural management environment based on existing structural analysis and reliability technologies. The impact on the ship acquisition management would be significant as it would allow the platform stakeholders a selection of figures of merit, upon which decisions can be based, and an accounting system for judging the acceptability of the structure. Current US Navy acquisition strategies do not incorporate quantitative structural operational performance measures and thereby do not adequately mitigate the programmatic risk of not meeting performance top-level requirements.

1.3 ORGANIZATION

This report consists of seven Chapters. Chapter 1 contains the background behind the need for structural performance metrics and an objective statement for this report. Elements of ship structural management are presented in Chapter 2 with regard to assuring acceptable performance of US Navy combatants using reliability-based performance metrics. Management of programmatic and technical risks is discussed in Section 2.1. Uncertainty in the parameters affecting performance is discussed in Section 2.2. Section 2.3 presents a discussion of structural reliability methodologies usable in support of quantitative performance metrics. The performance metrics proposed for use with ship or platform structures are presented in Section 2.4.

Chapter 3 presents the methodology for the development of reliability-based, performance metrics and top-level performance requirements. The development of failure definitions for use in reliability analyses is discussed in Chapter 4. Chapter 5 begins by describing the types of ship structural failure modes as reported in literature. These types are used to establish classes of failure modes, leading to a methodology for formulating the range of failure definitions. Failure definition examples are provided for traditional ship structural failure modes in Chapter 5 for the

hull girder and structural components at both the ultimate and serviceability types of failure. Summary tables of failure definitions are included.

Chapter 6 presents case studies to demonstrate the use and implications of the different performance metrics and their supporting reliability analysis methodologies. A notional Navy destroyer is the basis for the case studies. The hull is of conventional construction and design for a US Navy combatant, using longitudinally stiffened plating with transverse framing. The deckhouse is built from fiber-reinforced plastic (FRP) skin, balsa-core sandwich panels.

The first case study, found in Section 6.1, considers the top-level requirement that the deckhouse be capable of withstanding a lateral pressure load with some prescribed probability of survival. Section 6.2 presents the second case study, which demonstrates currently available methodologies for designing unstiffened plating against excessive permanent set, and the traditional limitations used to judge when failure has occurred. The third case study addresses the dependability associated with hull girder collapse failure during a specified mission in Section 6.3. The objective of the fourth case study, discussed in Section 6.4, is to reformulate the conventional cumulative damage, fatigue life prediction methodology in order to produce a more useable measure of the probability of crack initiation in support of a durability performance metric. Section 6.5 contains a comparison of the results of the case studies and provides the basis for determining their significance with regard to the importance of the particular failure modes. Concluding remarks and recommendations are made in Chapter 7.

CHAPTER 2 SHIP STRUCTURAL MANAGEMENT

2.1 RISK MANAGEMENT

The US Navy Acquisition Reform effort is presented as a means of reducing costs and risks in the acquisition process, while providing improved mission performance for Navy assets. The DD-21 Acquisition Program was an outgrowth of this desire, with the stated intent of shifting the burden of meeting the US Navy performance requirements to the competitive environment of the commercial sector and away from traditional military specifications. The attainment of the US Navy's performance goals by new designs is to be demonstrated by commercial design teams. These teams are to develop the assumptions and tools necessary to support the use of performance metrics and their associated acceptability thresholds. A principal role of the US Navy technical community is to certify the performance metric process and analysis results, and the conclusion of acceptability. Due to the absence of formal performance metrics, there remain unmitigated risks that the certification process will either approve an unacceptable design (consumer's risk) or reject an acceptable design (producer's risk). Both types of risk would negatively impact the US Navy acquisition process.

For the ship hull structure, a process has been developed to predict structural reliability: a formal, quantitative measure of performance. Reliability is defined here as the probability that a structural failure mode will not occur for a specified design environment and lifetime. The product of the failure mode probability and the failure consequence, or cost, provides a measure of technical risk, or expected loss. A reliability-based, acceptability process allows use of currently available technologies to produce a formal and traceable risk or performance measure for each identified failure mode. This report discusses the programmatic risk reductions inherent in adopting a reliability-based approach, by identifying the role of reliability in the development of operational performance metrics and acceptability criteria for ship structures.

Risk management is a project management supporting methodology used to minimize the likelihood of events that may impede a program's success. These undesirable events constitute program risks. The act of reducing the impact and likelihood of program risks to acceptable levels is termed risk mitigation. The *Continuous Risk Management Guidebook* (CRM) (Dorofee et al. 1996) defines risk as the possibility of suffering loss. This qualitative definition is commensurate with program risk. A second definition of risk is a measure of the probability and severity of adverse effects (e.g., Lowrance 1976). This quantitative definition may be regarded as technical risk. The CRM Guidebook considers risk management as a management practice with processes, methods and tools for managing risks in a project. It provides a disciplined environment for proactive decision-making to: assess continually what could go wrong (risks); determine which risks are important to deal with; implement strategies to deal with those risks; and measure effectiveness of the implemented strategies. The measure of effectiveness is considered in the form of risk metrics. Metrics are used to: measure attributes of a risk; provide meaningful information to enable more informed control decisions; assess the impact of success of a mitigation plan; and identify new risks. Risk metrics can be measures based on technical performance, schedule, cost or other identified program qualities. From an acquisition perspective, there are two general categories of risk: technical performance and programmatic. Programmatic risk refers to not meeting program schedules and budgets. Performance risk refers to not meeting the specified performance criteria or expectations. The degree to which performance is impaired is traditionally judged as a function of the design margins. Impact

magnitude associated with failure to meet operational performance requirements or expectations may be considered as 1) minimal or no impact; 2) small with some reduction in design margin; 3) acceptable with significant reduction in design margin; 4) large, no remaining design margin; and 5) significant. The specification as to what constitutes an acceptable design margin had not been specified for the DD-21 acquisition program, nor has a process been identified for mitigating the platform, structural performance risk associated with other US Navy acquisition programs.

A decision as to the acceptability or unacceptability of a system based on a risk or performance measure requires the setting of acceptance criteria. These criteria are threshold values, which delineate success or failure, or acceptable or unacceptable domains. Criteria are used for decisions regarding acceptance of new designs, changes to existing systems, or a means of ranking different options. Criteria may also provide elevated goals for designers, different than those used for acceptance, such that a more optimal design may result.

The traditional form of structural acceptance criteria is deterministic in nature. Deterministic criteria attempt to neutralize the influence of uncertainty by arriving at some safety margin, or factor of safety, with the intent of designing the structural system for a higher performance, or lower risk, than required by the actual threshold delineating acceptable and unacceptable domains. This is a simple approach allowing rapid design and analysis of systems. Some drawbacks are the lack of clarity in all assumptions, and the inability to update the criteria with greater system knowledge. Deterministic approaches are founded in tradition and experience, and are useful for simple decision-making, but assure an unknown level of safety.

Probabilistic criteria require explicit modeling of the system in question. The inclusion of uncertainties and dependencies is a way of addressing the uncertainty by modeling the likelihood of an undesirable event. This method requires an understanding of the risk-generating processes and can produce a quantitative or qualitative measure. The ability to update the process with new knowledge makes this technique preferable to deterministic techniques, but not everything is easy to quantify. Conversely, the amount of information required for accurate results is much greater than for a traditional, deterministic approach.

Probabilistic risk assessment requires the determination of potentially hazardous scenarios, the likelihood of the scenario and the associated consequences. The resulting measure of risk, or change in risk, may be considered the expected loss. This expected loss could then be compared to the governing criteria to decide acceptability. A performance-based assessment considers measures such as *reliability*, *availability*, *maintainability*, *capability*, *efficiency*, *repairability*, *producability* and *dependability*.

Criteria are used for the decisions regarding the acceptability of a system such as those imposed by government regulation and must address issues such as:

- How safe is safe enough?
- Will this design perform to an *acceptable* level?
- Will this change to the existing system affect the system risk or performance in a *significant* manner?

Criteria are developed for use in design optimization to assure that the needs of the customer are met. Such criteria assist the design management team in defining the

performance/risk goals such that they do not limit the designers, nor significantly exceed the required levels of safety as prescribed by regulations.

Acceptability of a certain level of risk or performance requires the mapping of the decision maker's judgment and values into an expression, which is comparable to a quantitative or qualitative measure of the system or process in question. The decision-maker represents the society and individuals who may be impacted by the decision. The measure may be considered either qualitative (subjective) or quantitative (objective). Qualitatively, the criteria must take into account the need for the risk exposure, the amount of dependable controls over the risk producing process, and the fairness in which the costs, risks and benefits are distributed (Reid 1992). Quantitatively, the criteria must take into account uniformity of standards and efficiency (Reid 1992). Modarres (1993) proposes that fair, balanced and consistent risk criteria must be based upon comparison of the risks and benefits associated with certain activities. Strict quantitative criteria are in the risk or performance domain characterized by quantitative system analysis, which produces a measure with physical meaning. The risk is presented as an expected loss, calculated as the product of the frequency and consequences of the event. Such criteria are based on technical analysis, and do not necessarily address value judgments.

Absolute criteria are independent limiting values, which reflect the worldview of the system analysts. Absolute criteria used for judging new systems provide a fixed bound for the acceptable domain. The absolute value predicted by the analysis is comparable to measures of other systems only if all uncertainties and contributors have been identified. The choice of "one-in-a-million" as the criterion governing acceptable risk is an example of an absolute quantitative limit without added conditions (Modarres 1993), whereas the "as-low-as-reasonably-possible" criterion is qualitative without need for comparison (Melchers 1995).

By quantitatively assessing similar systems (which are deemed to represent acceptable risk levels) in the same context and matching new designs to the calculated levels, relative criteria may be developed. This is a calibration of the new tool to existing practice, which has been popularized in structural reliability-based design code formulation (Melchers 1995). The coarseness of the structural system models used for design requires a similar coarseness in the criteria. The result is a means of assuring that at least a certain level of risk, or failure probability, is not exceeded. These types of calibrated criteria, currently being developed by the US Navy, are reliability-based design guidelines embodied in a Load and Resistance, Factor Design (LRFD) format (Ayyub et al. 2002). LRFD criteria are analytical, closed form checking equations with partial safety factors developed through the use of structural reliability analysis methodologies of varying sophistication. These guidelines are being developed using current, US Navy load and strength prediction methods and information, and consider only traditional structural materials and configurations for a limited range of structural failure modes. Though limited, they represent a significant shift in the manner of conducting designs and assessing design acceptability from traditional approaches and form a framework from which new ship structures and materials may be addressed. This work can be extended and expanded so that the structural performance risks associated with new US Navy ship acquisitions are mitigated, by quantitatively ensuring acceptable levels of performance as compared to past experience.

The DD-21 program represented a change from traditional acquisition and design of US Navy surface combatants leading to higher levels of risk and uncertainty. The DD-21 and follow-on ships, such as the DD(X), are being designed to operate at high speeds in severe environments for longer durations, carry increased payloads, be more survivable and have

reduced acquisition and life-cycle costs. These goals require new technologies, loadings, materials and configurations that involve a large degree of risk and uncertainty in their implementation. The degree to which the stated performance goals are achieved is left to the commercial designer, while acceptance of the resulting design is the responsibility of the US Navy technical community. To minimize the risk of certifying an unacceptable design or rejecting an acceptable design, performance metrics and associated acceptability criteria are recommended which would consider performance goals and design margins in a reliability-based format. The reliability-based guidelines currently in development by the US Navy require extensions to encompass new structural failure modes, materials, configurations, and analysis technologies. Use of this new technology by industry designers working in collaboration with the Navy technical developers would create a reliability-based design and acceptability process in an efficient and effective manner. Rigorous and traceable consideration of structural failure modes in a reliability framework allows formalized, quantitative risk-based decision making, effectively mitigating programmatic risks.

2.2 UNCERTAINTY

2.2.1 General Uncertainty Characterization

There has been much work done in many different disciplines to develop methods for classifying and quantifying types of uncertainties found in physical system models and their basic variables (Ayyub 1992 and 1994; Ayyub and Lai 1992; Ayyub and McCuen 1997; Brown 1979a and 1979b; Cai 1996; Chao 1995; Gupta 1992; Ibrahim and Ayyub 1992; Klir and Folger 1988; Kruse et al. 1991; Twisdale 1979). Klir and Folger (1988) define two general classes of uncertainty as ambiguity and vagueness. Ambiguity may also be considered objective or non-cognitive, while vagueness may be considered subjective or cognitive.

2.2.1.1 Ambiguity

The ambiguity type of uncertainty is considered the result of non-cognitive sources such as (1) physical randomness; (2) statistical uncertainty due to use of limited information to estimate the characteristics of these parameters; and (3) modeling uncertainties due to simplifying assumptions in analytical and prediction models, simplified methods, and idealized representations of real performances. Ambiguity associated with the physical behavior (mechanisms) in structural reliability predictions is and has been the subject of much research (for example, Ang and Tang 1975 and 1990; Ayyub and Haldar 1984b; Daidola and Basar 1980; Galambos and Ravindra 1978; Hess et al. 1994; Hess et al. 1997; Hughes et al. 1994; Mansour and Faulkner 1973; Mansour 1993; Nikolaidis and Kaplan 1991; Schrader et al. 1979; Thoft-Christensen and Baker 1982; White and Ayyub 1985; White and Ayyub 1993). The uncertainties associated with the load and structural response or strength predictions and the basic variables upon which these predictions depend may be considered to be of the ambiguity type.

Probability theory is effective for characterizing the uncertainty of the basic variables, X_i and relies on the use of probability density functions (PDFs). Probability density functions have the following properties (Ayyub and McCuen 1997):

$$f_X(x) \geq 0 \quad \text{for all } x; \tag{2-1}$$

$$\int_{-\infty}^{\infty} f_X(x)dx = 1; \tag{2-2}$$

and

$$P(a < X < b) = \int_{a}^{b} f_X(x)dx \tag{2-3}$$

Using current deterministic methods, the design strength of a structure is based on nominal values of basic strength variables, both material and geometric, such as yield strength of the material, plate thickness, modulus of elasticity, and so forth. Random behavior of the basic strength variables can cause the strength of the structure to vary beyond acceptable levels. The use of structural response predictions in a reliability-based design format requires accurate characterization of the uncertainty inherent in the basic strength and load variables. Preceding the development of any reliability-based design procedure, relevant variables must be identified and their statistical characteristics defined. As shown in Hughes et al. (1994), the strength prediction of a longitudinally stiffened panel may be shown to have coefficients of variation ranging as high as 10%. Quantifying the uncertainty, or randomness, found in the basic strength variables allows the designer to account for this variability in the strength of the structure. The uncertainty associated with the strength prediction may be estimated using simulation techniques, such as Monte-Carlo simulation, which allow the values for the basic strength variables to be generated based on their statistical distributions (probability density functions). Hess et al. (1997) expanded the available database and performed analyses to better statistically characterize the uncertainty for material and geometric basic strength variables as used in naval ship construction. These basic variables require continued investigation to maintain accuracy over time and to decrease the uncertainty surrounding their probabilistic characterizations, particularly with the introduction of new materials, configurations and operation.

2.2.1.2 Vagueness

The vagueness type of uncertainty is the result of cognitive sources such as (1) the definition of certain parameters, for example, structural performance (failure or survival), quality, deterioration, skill and experience of construction workers and engineers, environmental impact of projects, conditions of existing structures; and (2) inter-relationships among the parameters of the problems, especially for complex systems. Treatment of vagueness or cognitive uncertainties has been discussed in Alvi, Lai and Ayyub (1992), Brown (1979a and 1979b), Chao (1995), Dong et al. (1989), Furuta (1994), Gupta (1992), Klir and Folger (1988), Shiraishi and Furuta (1989) and Yao (1980).

The uncertainty associated with defining the structural change in state from complete survival to complete failure may be considered to be a form of vagueness uncertainty. Reliability predictions are highly dependent upon the underlying level of damage and the uncertainties associated with the failure definition. The acceptable levels of damage for one system may not be acceptable at all for another. Allowances for vagueness in the failure mode definition provides the designer with a procedure for incorporating subjective judgment into the design process. This uncertainty, or vagueness, is due to lack of knowledge of the component's function in the system context and the impact of degradation on the parent system. Capturing and quantifying vagueness requires the application of measures which can deal with subjective

information. Two different theories may be used in this regard: possibility (fuzzy set) theory and subjective probability (Bayesian) theory.

2.2.2 Basic Variable Uncertainty

The uncertainty in basic strength variables can be quantified using two types of *bias*. The *ratio* bias and the *difference* bias. The *ratio* bias is the ratio between the measured value and the nominal (or design) value for strength variables as follows:

$$b_R = \frac{\text{measured value}}{\text{nominal value}} \tag{2-4}$$

The "difference" bias is the difference, or error, between the measured value and the nominal value:

$$b_D = \textit{measured}\text{ value} - \text{nominal value} \tag{2-5}$$

For geometric variables such as thickness, breadth and height, variations from nominally specified values may not depend upon nominal values. For small nominal values of these variables, the ratio bias may overestimate the variability, while for larger variable values, it may underestimate the variability. Therefore the error, or difference, between the measured and nominal values can be analyzed along with the ratio of these values.

Uncertainty in distortion, or eccentricity, can be described using a normalized value, which is the ratio of the distortion to a dimension of the distorted structural component. An example in this case is the normalization of stiffener distortion by the stiffener length.

2.2.3 Modeling Uncertainty

The values of structural strength, R, and the applied loads, L_i, used in design are calculated based on characteristic, or nominal, values of the basic variables on which the prediction depends. These characteristic values may also be considered *rules* values. The uncertainty in the prediction model may be considered a bias. The bias is the ratio of the real value to the rules prediction, multiplied by the rules prediction as part of the limit state equation. The bias takes the form:

$$B^R_{Real/Rules} = \frac{R_{\text{Real}}}{R_{\text{Rules}}} = \frac{R_{\text{Real}}}{R_{\text{Experimental}}} * \frac{R_{\text{Experimental}}}{R_{\text{Advanced Prediction}}} * \frac{R_{\text{AdvPred}}}{R_{\text{Rules}}} \tag{2-6}$$

The four levels of prediction model may be outlined as follows:

- Rules: predicted value as used in the LRFD limit state equation.
- Advanced Prediction: value predicted through the use of the best available numerical or analytical techniques.
- Experimental: value determined through experimental testing.
- Real: values that may happen during a ship's life.

The modeling bias equation for strength may be rewritten as:

$$B_R = B^R_{41} = B^R_{43} * B^R_{32} * B^R_{21} \tag{2-7}$$

And for load predictions the modeling bias may be written as:

$$B_L = B_{41}^L = B_{43}^L * B_{32}^L * B_{21}^L \tag{2-8}$$

2.3 STRUCTURAL RELIABILITY

Surface ships encounter numerous loads (for example, wave bending, whipping, slamming) whose magnitudes and times of occurrence are highly uncertain. Some of these loads or combinations of loads are capable of damaging the ship's structure, possibly severely. Damage often results in a reduction or loss of structural integrity, or otherwise adversely affects ship system performance. Traditional design criteria attempt to guard against the possibility of structural damage and ship system degradation and failure by imposing deterministic safety factors into the design equations, tempered by engineering judgment. These safety factors, or design margins, have evolved over time and are highly correlated to the predictive tools and design domain for which they were established. The design margins are subjectively derived, quantitative evidence of the uncertainty inherent in design. A change to either the tools or domain requires a change to the design margin. Unfortunately, with less reliance on engineering judgment, the traditional criteria often provide an undetermined level of safety and performance, which, experience has shown, is not always adequate, even for traditional ship structural configurations. This inadequacy will only be heightened with the use of new design approaches beyond the traditional design domain, where implicit assumptions in the criteria no longer apply, and with the increasing demands of multiple, competing design and performance objectives as envisioned for future US Navy ships.

Criteria based upon explicit, first principles methodologies which incorporate structural reliability theory are an effective, formal and traceable manner in which to consider and create new designs. Structural reliability methods allow the prediction of occurrence likelihood for a particular event of interest (such as structural failure), allowing the designer to limit the probability of undesirable events. Calculating the probability that a failure event will not occur provides a performance measure termed reliability.

In reliability predictions of electronic or mechanical systems, much of the work has been carried out with the extensive use of failure databases, which allow the prediction of the mean-time-to-failure (MTTF), mean-time-between-failures (MTBF), or failure rate, for each component of the system. Combining the failure rates of all the components to arrive at the system failure rate provides a means for finding the reliability of the system (Ayyub and McCuen 1997; Kumamoto and Henley 1996; Modarres 1993). Studies such as Hawkins et al. (1971), Jordan and Cochran (1978), Jordan and Knight (1979), and Akita (1982) provide the beginnings of a structural failure database for ship structures for use in this manner. Extensive testing of details for both fatigue and strength has provided a means by which the reliability of similar structural details may be predicted. This approach has lead to catalogs of structural details and members for use in design.

The extensive range of structural configurations and the large costs of testing at a statistically significant level have contributed to the development of structural reliability theory from an approximate "physics of failure" perspective. This approach propagates basic (input) variable uncertainty through an approximate model of the system under inspection, to provide the analyst with an estimated likelihood that the load will exceed the structural strength, over the designated lifetime and under predetermined operating conditions.

Structural reliability theory has been developed with the assumption of crisp delineation between success and failure, and this approach has been carried into application to structural systems. The classical performance function is $Z = R - L$, where R represents the available resistance and L represents the load effect. The failure event is considered to be when $Z < 0$, or when the load, L, exceeds the resistance, R (Ang and Tang 1990; Ayyub and McCuen 1997; Thoft-Christensen and Baker 1982; Madsen et al. 1986; White and Ayyub 1985). This failure definition traditionally depends upon a resistance model which represents the ultimate strength of the structural component where the component is unable to carry any increase in load and is considered to have failed. Other non-strength related failure modes may also considered in this format, such as excessive vibration, deformation, or deflection.

The strength and load variables in the performance function represent random variables whose values depend upon a probability density function (PDF) developed using predictive tools and input values called basic random variables and characterized using PDFs. Solving for a probability of failure, involves solving the following interval:

$$P_f = \int_{-\infty}^{0} f_Z(z)dz \tag{2-9}$$

where $f_Z(z)$ is the PDF of the performance function, Z.

Traditionally, three reliability assessment methods are discussed and used in structural reliability predictions. These are referred to as Levels 1, 2 and 3, with complexity and amount of required information increasing with level number. (For information on the different levels and an explanation of the theory see Ang and Tang (1990); Madsen et al. (1986); Mansour (1990); Thoft-Christensen and Baker (1982); White and Ayyub (1985).) Descriptions of these will be given below.

2.3.1 Level 1 Load and Resistance Factor Design

Level 1 reliability methods are design equations that use load and resistance, partial safety factors, developed with the use of higher order reliability methods. The partial safety factor format allows the implied reliability levels to be hidden from the designer. The factors may also be developed without use of reliability methods and are an extension of the traditional, factor of safety design approach. The Load and Resistance Factor Design (LRFD) format is a Level 1 structural reliability method in the following form:

$$Z = \phi\, R - \sum_{i=1}^{n} \gamma_i\, \mathrm{L_i} \quad \mathrm{i = 1....n\ \ (n\ different\ load\ types)} \tag{2-10}$$

To achieve a successful design, Z must be greater than or equal to zero. Therefore, the new form of the general LRFD equation is:

$$\phi\, R \geq \sum_{i=1}^{n} \gamma_i\, L_i \quad i = 1....n\ \ (n\ \text{different load types}) \tag{2-11}$$

where ϕ is the strength partial safety factor or strength reduction factor, (<1); R is the predicted strength; γ_i is a load partial safety factor or load magnification factor (>1); and L_i is a predicted load. When the factored strength equals the factored load, a predetermined reliability requirement is considered to be met or exceeded. The strength of the Level 1 approach is that

the designer can efficiently use a reliability-based, LRFD code without potential errors resulting from the complexity of the higher-level reliability techniques.

Reliability-based, LRFD codes are currently in use by the American Institute of Steel Construction (AISC 1993), American Association of State Highway and Transportation Officials (AASHTO 1998), American Petroleum Institute (API 1993), and the Norwegian Technology Standards Institution (NORSOK 1998). Discussion of Level 1 methods and their development may be found in structural reliability texts and papers including Lee and Son (1989), Madsen et al. (1986), Mansour (1990), Thoft-Christensen and Baker (1982), White and Ayyub (1985).

2.3.2 Level 2 Approximate Methods

Level 2 methods consist of an approximation made of the reliability using a Taylor series expansion. Level 2 approximate methods that use only the means and variances of variables in the limit state equation to predict the reliability are termed First Order Reliability Methods (FORM). Extensions to FORM have been developed to allow approximate inclusion of the basic variable probability density functions. This modified approach is termed the Advanced Second Moment (ASM) method and can provide a substantial increase in accuracy. Relative to a higher level reliability method, the reduction in needed information for a Level 2 reliability analysis makes it quite appealing and so it is frequently used. Level 2 methods are discussed in structural reliability texts and papers including Ang and Tang (1990), Ayyub and Haldar (1984), Ayyub and McCuen (1997), Chao (1995), Der Kiureghian, Lin and Hwang (1987), Hasofer and Lind (1973), Madsen et al. (1986), Mansour (1990 and 1993), Modarres (1993) and White and Ayyub (1985).

The Advanced, Second Moment (ASM) method is an algorithm, which calculates the safety index in the reduced, normal space. Non-normal basic variables are transformed to equivalent normal variables by matching the probability density, and cumulative density functions at a specified value of the random variable. According to the ASM formulation, the safety index (β) is the minimum distance from the origin to the limit state surface in the reduced coordinates space. The vector designation of β is known as the design point, or Most Likely Failure Point (MLFP) with the coordinates of (R^*,$\underline{L}^*$). The development and history of this method are discussed in Ayyub and Haldar (1984), Mansour (1990), and White and Ayyub (1985).

The strength and load elements of the performance functions discussed in the preceding sections are basic variables or functions of basic variable. If the basic elements of the performance functions are R and L_i as shown in Equation 2-12, their means, standard deviations and distributions must be specified for use in the reliability assessment.

$$Z = R - \sum_{i=1}^{n} L_i \qquad (2\text{-}12)$$

where R is the strength, and L_i is the i^{th} load prediction (such as stillwater, wave or whipping response).

The strength and loads are developed from predictive models in which the uncertainty in the basic variables may be propagated. One may either assign a fixed, mean predictive value with an accompanying uncertainty (such as the mean strength from the model is 25,000 lbs with a 10% COV), or insert the model used to generate the predicted value into the performance

function. The basic variables upon which the predictive model depend are then uncertain variables with an accompanying uncertainty, explicitly treated in the performance function. Inclusion of the basic variables of each predictive model in Equation 2-12 results in a more complex performance function as shown in Equation 2-13.

$$Z = R(x_{R_1}, x_{R_2}, x_{R_3}, \ldots x_{R_n}) - L(x_{L_1}, x_{L_2}, x_{L_3}, \ldots x_{L_n}) \tag{2-13}$$

The most general form of the performance function is:

$$Z = g(x_1, x_2, x_3, \ldots x_n) \tag{2-14}$$

The random variable vector $\underline{X}$ can represent the basic variables from all predictive models used in the performance function. The likelihood of $Z < 0$ can be assessed using ASM as described in Ayyub and McCuen (1997), Ang and Tang (1990), Madsen at al (1986), Mansour (1990).

The ASM algorithm is as follows (notation from Ayyub and McCuen 1997):

1. Assume an initial design point, x^*, as the mean values of the basic variables.
2. Calculate the equivalent normal distributions (μ_X^N, σ_X^N) for the non-normal basic variables by matching the probability density function, $f_X(x)$, and the cumulative density functions, $F_X(x)$, of the basic variable with the standard normal distribution as shown in Equations 2-15 and 2-16 at the coordinate for the design point, x^*.

$$\mu_X^N = x^* - \Phi^{-1}[F_X(x^*)]\sigma_X^N \tag{2-15}$$

$$\sigma_X^N = \frac{\phi\left(\Phi^{-1}[F_X(x^*)]\right)}{f_X\left(x^*\right)} \tag{2-16}$$

3. Evaluate the directional cosines (α^*) at the design point (x^*):

$$\alpha_i^* = \frac{\left(\frac{\partial g}{\partial x_i}\right)_* \sigma_{x_i}^N}{\sqrt{\sum_{i=1}^{n}\left[\left(\frac{\partial g}{\partial x_i}\right)_* \sigma_{x_i}^N\right]^2}} \tag{2-17}$$

4. Set the performance function equal to zero and solve for β:

$$g\left[\left(\mu_{X_1}^N - \alpha_1^* \beta \sigma_{X_1}^N\right), \left(\mu_{X_2}^N - \alpha_2^* \beta \sigma_{X_2}^N\right), \ldots, \left(\mu_{X_n}^N - \alpha_n^* \beta \sigma_{X_n}^N\right)\right] = 0 \tag{2-18}$$

5. Using β found in Step 4, calculate the coordinates of the new design point, x^*, where:

$$x_i^* = \mu_{X_i}^N - \alpha_i^* \beta \sigma_{X_{i1}}^N \tag{2-19}$$

6. Return to Step 2 and repeat until β has converged.

The ASM algorithm allows the prediction of the safety index, β, which represents an approximation to the probability of failure according to the following transformation:

$$p_f = 1 - \Phi(\beta) \tag{2-20}$$

where $\Phi(\beta)$ represents the standard normal distribution with a mean of zero and a standard deviation of 1.0. Table 1 shows the probability of failure associated with safety indices ranging from 1.0 to 7.0. Software is available to evaluate the safety index using ASM as discussed in Mansour (1990). Evaluation of the appropriateness of such tools should be based upon the performance function being considered. It is perfectly reasonable to do most of the analyses in the context of spreadsheets such as Microsoft Excel (2000), where iterations may be conducted manually, yet the process remains traceable in the future.

Table 1. Safety Index, β, Conversion to Probability of Failure

β	p_f
1	0.1587
2	0.02275
3	0.00135
4	3.17E-05
5	2.87E-07
6	9.9E-10
7	1.29E-12

The safety index is easily derived in a closed form, in the case of normally distributed variables and a linear performance function. The safety index may be calculated for $Z = R - L$ as follows:

$$\beta = \frac{\mu_R - \mu_L}{\sqrt{\sigma_R^2 + \sigma_L^2}} \tag{2-21}$$

where μ_R is the mean resistance, μ_L is the load effect mean, σ_R is the standard deviation of the resistance and σ_L is the standard deviation of the load effect. The safety index can also be presented as a function of Z, with parameters μ_Z and σ_Z.

$$\beta = \frac{\mu_Z}{\sigma_Z} \tag{2-22}$$

2.3.3 Level 3 Fully Probabilistic Methods

Level 3 reliability assessment uses complete probabilistic characterizations of all basic load and strength variables to capture the uncertainty inherent in the strength and the load predictions. A popular method of solving this problem is Monte Carlo simulation as closed form solutions to the convolution integral are rarely possible for realistic analyses. Ayyub and Haldar (1984) used conditional expectation and antithetic variates, variance reduction techniques for structural reliability assessment. Ayyub and Lai (1989) discuss simulation techniques with Latin Hypercube Sampling. Other techniques are possible such as importance sampling as outlined in Ang and Tang (1990), Bjerager (1988), Casciati and Faravelli (1980), and Harbitz (1986).

2.3.4 Level 4 Technical Risk

The inclusion of technical risk in an analysis or design is informally considered Level 4 (Madsen et al. 1986). To achieve this quantitatively, probability of occurrence must be attached to the failure event and the consequences corresponding to the failure must be identified and assigned some value. The technical risk measure would be the product of the probability of failure and the failure consequences.

The idea of calculating the technical risk, or expected loss, associated with a structural design, is to provide a normalized value that is transportable beyond the specific system, sub-system, or component under study for consideration in a larger context. For comparison or aggregation of structural sub-systems, a metric is needed. This metric may be found in the prediction of risk. The acceptable reliability levels associated with structural components throughout a structural system may not be constant, but could vary as the importance of the components varies. This importance may be measured by jointly considering the consequences and likelihood of component failures, thereby providing the technical risk associated with the component.

An example of structural failure is the deformation of an unstiffened plate. Deformation may occur elastically or plastically resulting in temporary or permanent displacement, respectively. Excessive permanent set may misalign some mechanical system rendering it inoperable; reduce the strength of a larger structural system beyond acceptable levels and endanger more critical systems; violate signature control restrictions; or be cosmetically unappealing. The consequence of the permanent deformation may also be an increase in the likelihood of greater system failures. The point at which the deformation level becomes unacceptable for the designer, owner or surveyor is the onset of failure for the plate. The failure definition for the permanent set of unstiffened plating depends upon the acceptability of the consequences of the permanent set. When the consequences are no longer acceptable, the plate has failed. A designer attempts to limit the likelihood of the plate experiencing such plastic deformation. The probability that the plate does not exceed some specified value of permanent set is the reliability. A criterion must be set for this failure mode. A deterministic criterion would enforce a limiting value on the permanent set, without considering any restriction on the probability of this limiting value being exceeded, nor addressing uncertainties in the calculation. In this case, the risk of failure would be unknown, though a design margin may be applied based on engineering judgment. An alternative approach would be to calculate the reliability associated with this failure mode for a specified level of permanent set and compare it to a technical risk-based, reliability criterion to judge design acceptability, formally and traceably accounting for uncertainties in the process.

2.4 SYSTEM PERFORMANCE METRICS

For onboard ship systems, mission readiness is determined using the performance goals: Operational Capability, Operational Dependability and Operational Availability. Currently, in ship design and life-cycle management, a formal, quantitative linkage does not exist between the ship structural operational performance and specific readiness and performance goals. The methodology proposed in this report will provide a linkage between top-level readiness requirements and the ship structure. Case studies are provided to demonstrate important aspects of this application.

Each performance parameter mentioned above is discussed in Department of the Navy, Office of the Chief of Naval Operations Instruction OPNAVINST 3000.12a "Operational Availability Handbook Draft" (OPNAV 2001) as a figure of merit (FOM) for use in the acquisition and life-cycle management processes. A FOM is a formal metric that is understood by the system stakeholders, and as such, it must be quantitative. For the top-level structural managers, the need is for an understanding of the operational performance of the system. According to 3001.12a (Draft), the probability that the system can counter a threat, or resist a demand is the operational capability (Co). The probability that the system can complete a mission given that it has started successfully is the operational dependability (Do). This is also sometimes called the mission reliability. The probability that the system is up and ready to perform as intended is the operational availability (Ao).

System Effectiveness (SE) is used for decision-making with regard to acquisition and life-cycle management of platform-based systems. According to OPNAVINST 3000.12 (OPNAV 1987), SE is a function of:

- Operational Capability (Co):
  - "...The ability to counter the threat, in terms such as probability of kill, exchange ratios, etc."
  - For the platform, this would imply the ability to resist demands in the form of environmental, operational and combat loads, given a realistic/conservative model of the platform system at the time of demand.
- Operational Availability (Ao):
  - "...probability that a system is up and ready to perform as intended."
  - For the platform, this is the probability that the system will function at an acceptable level when operated using a prescribed maintenance (inspection and repair) program over its life.
- Operational Dependability (Do):
  - "... probability that a system is able to complete a mission that it has started." Also referred to as "mission reliability".
  - For the platform, this is the probability that the system will function at an acceptable level for a specified, short-term mission, without excessive maintenance.

The overall System Effectiveness is shown to be the product of these measures: SE = Co x Ao x Do. This relatively simple measurement of system effectiveness has not been included in draft OPNAVINST 3000.12a (OPNAV 2001).

Draft OPNAVINST 3000.12a is being written to address development and tracking of Ao throughout a system life cycle. It addresses mechanical and electrical systems as they would exist on naval platforms such as aircraft and ships. These performance measures are therefore conditioned on the platform performance being acceptable such that the platform is available for the mission, can survive the mission, supports the performance of dependent systems (e.g., mechanical or electrical) and does not degrade excessively. Formal metrics similar to those found in draft OPNAVINST 3000.12a do not exist to support the design and management of surface ship structural operational performance. The primary focus of this report is to introduce such metrics.

The metrics Ao, Do and Co represent quantitative representations of the performance required from a system. The measures are developed to answer specific questions about the ability of the system to satisfy stated needs. The three questions which govern a ship structural design in a performance-based decision environment could be:

1. To what degree does the structure perform its functions? For example, will the structure successfully resist the expected threats and loads, and will it successfully support dependent systems? The answer can be considered the system capability.
2. Given that the structure is intact at the beginning of a mission, what is the likelihood the structure will successfully function during a prescribed mission, with no repair? The answer can be considered the system dependability, or mission reliability.
3. What is the percentage of time that the structure is available for a mission and not undergoing repair? The answer can be considered the system availability.

The answers to these questions should preferably be quantitative measures to allow for comparison to acceptability criteria, similar to the use of Ao, Do and Co for mechanical and electrical systems. Such measures have not been developed for use in the management of surface ship structural systems.

The measure of the degree to which a ship structure performs its functions is traditionally addressed using factors of safety and design margins. If the resistance is greater than the load by a prescribed amount, then the structure is deemed satisfactory. The design margins are based on traditional, implicit performance needs and cannot be adjusted to account for new structural technologies or changes to performance requirements. The use of a static design margin does not allow for a true assessment of the performance of the structure, nor does it allow for proper mitigation of structures-related risks. The adoption of an explicit measure of operational performance is warranted. Quantitative assessment methodologies exist for ship structures, and allow the analyst to determine the structural probability of failure and conversely the associated reliability. Ship structural reliability is the ability of the ship to successfully perform its functions for a stated period of time under prescribed environmental conditions. While usually considered mainly in the context of risk and safety, the prediction of ship structural reliability provides an explicit measure of the structural performance. The manner in which the structural reliability prediction is developed may be modified to support prediction of capability, dependability and availability.

The purpose of these operational performance measures as applied to ship structures may be summarized as follows. The operational *durability* performance measure to be defined in detail later is the probability that the platform structure will not require repair over its lifetime.

This serves the purpose of providing the likelihood that the ship structure will be ready for a mission when called upon and provides information helpful for determining operational availability. The operational *dependability* of the ship structure is defined as the probability that the ship structure will "be there" for the mission, once the mission begins. This measure provides a quantitative level of assurance that once the mission has started, the structure will not hamper the ship from navigating the seas as needed while successfully resisting the seaway loads. The operational *capability* of the ship structure is the ability of the structure to support operational needs aside from those associated with "being there" in the face of seaway loads. Structural capability will refer to performance associated with combat loads and accidental loading, and supporting dependent, non-structural systems.

The development of these three performance parameters for ship structures is important to support risk and performance-based management. Operational performance metric definitions will be further developed in Sections 2.4.1, 2.4.2 and 2.4.3 to support advancement of ship structural design and management into a performance-based environment. Existing structural reliability methodologies will be shown to support the proposed performance metrics. Operational performance is considered exclusively in this report. The performance of the structure in a damaged state may be assessed using this methodology but is not explored here. Other forms of performance such as *robustness*, *maintainability*, *efficiency*, *repairability*, and *producability* are not included in this report as they are not operational measures such as are discussed in OPNAVINST 3000.12, but measure the supportability of the structure over its lifetime. Availability will be addressed in Section 2.4.2.

The failure modes most associated with each performance measure can be developed given their significance with regard to the performance of interest. In general, all failure modes should be considered in measuring performance, but practically speaking only those of greatest significance will need special focus for a particular performance metric. Taken together, the three operational performance measures described above will capture the failure modes traditionally considered in ship structural design.

Combination of the performance measures into one measure of system effectiveness is not recommended due to dependencies between the proposed performance metrics. OPNAVINST 3000.12 (OPNAV 1987) proposes defining the System Effectiveness (SE) as SE = Co x Do x Ao. The Draft version of OPNAVINST 3000.12a (OPNAV 2001) does not include this approach and prefers maintaining separation between the metrics. The platform managers use the metrics associated with electrical and mechanical systems to address a range of customer needs. Ao helps determine the logistical pyramid in support of the system. Co helps determine the effectiveness of the system in operational simulations. Do allows the manager to make strategic decisions as to how many systems are required for a particular mission, and ensure adequate coverage.

2.4.1 Operational Capability

Operational capability performance of the structure will be defined here as the ability of the structure to support the combat mission requirements that do not include general operability performance of the ship in a seaway environment. Such requirements will include such things as supporting signatures control and effective resistance to weapons effects. Other requirements could include robustness in the face of accidental loads or sufficient strength to resist aircraft

operations. Structural Operational Capability (Co') can be defined as the probability that a ship structure performs successfully given the following information:

- Loads and load effects that may be considered include weapons effects, accidental loads, operational loads and seaway loads.
- Structural scantlings are conservatively reduced to account for possible degradation.
- System failure is defined as unacceptable decreases in support for dependent systems.
- No maintenance actions are included.
- No structural degradation mechanisms are included in the calculation, such as corrosion, wear or fatigue.

The operational capability of a structure can be measured using structural reliability methods. The analysis proceeds by assuming the load will occur, either over the ship's life as in wave loads, or as a given event at a certain instant in time. The deformation of unstiffened plates due to lifetime wave loading can impact the capability of the ship to maintain minimal radar signatures. This type of capability performance is considered in the case study presented in Section 6.2. For single load events, the probability that the structure fails as a result of the loading is developed as a conditional probability. The calculated probability of failure is conditioned on the probability of the load occurring, which in this case is 100%. This type of calculation can be considered a fragility analysis. A case study will be presented in Section 6.1, demonstrating the capability of a fiber-reinforced plastic (FRP) composite panel to withstand a prescribed pressure load.

The Structural Operational Capability (Co') relies on design values for load and strength information, and is not a function of time. These design values are conservative and should include the predicted effects of degradation occurring during the design life. The design load can be either a lifetime load distributon or of the once-in-lifetime variety. To consider matters of life extension or remaining life, the design Co' can be updated in the future. Use of real input values for determining Co', would give an instantaneous measure of Co'.

2.4.2 Operational Dependability (Mission Reliability)

For the platform, the Operational Dependability (Do), or mission reliability, is the probability that the system will function at an acceptable level for the duration of a mission without excessive degradation. Structural Operational Dependability (Do') can be defined to be the probability that a ship structure performs successfully given that the structure is in an acceptable, functioning state at the start of the mission. Structural reliability-based analyses support the prediction of this performance measure. The analyses will be based upon the following information:

- Seaway wave loading is considered in the frequency domain, for a specified severe, short-term mission.
- The structural scantlings used in the analysis are the original, as-built scantlings conservatively reduced by amounts in keeping with corrosion or other time-based degradation mechanisms.

- System failure is defined as unacceptable decreases in structural integrity and support for dependent systems.
- No maintenance occurs during the mission.
- Structural degradation mechanisms can be included for the duration of the mission.

The mission reliability is primarily concerned with overload failures, or failures resulting from extreme environmental loads to be expected from a mission profile chosen to challenge the integrity and safety of the structure. Collapse, buckling, and fracture will be some of the failure mechanisms important to determining the mission reliability. A case study will be presented in Section 6.3 for the prediction of Do' for the overload failure of a ship hull girder.

2.4.3 Operational Durability

For the platform, the Operational Availability (Ao) is the probability that the system will function at an acceptable level when operated using a prescribed maintenance (inspection and repair) program over its life. For the structure, Ao is defined as the percentage of time the structural system is ready for use or being used. The down time of the structure results from being dockside or in dry-dock. Such occasions are for ship replenishment, inspection and repair and are outside the normal domain of the ship structural designer. As a result, maintainability and supportability models have not been developed sufficiently to support measuring "operational" availability for a ship structure. Until this occurs, a placeholder must be established to support the decision process with regard to economically minimizing downtime.

The adjective "durable" is defined as being "capable of withstanding wear and tear or decay" (American Heritage Dictionary 1982). The National Research Council discusses reliability concepts as they apply to logistics concerns (NRC 1999), and defines durability as:

> "The probability that an item, component or system will successfully survive its projected service life, overhaul point, or rebuild point without a catastrophic failure. (A catastrophic failure is a failure that requires that the item, component, or system be rebuilt or replaced.)"

From these definitions, a durability performance metric, Ao', may be developed to measure the degree to which the structural system remains useable and not in need of repair over a specified period of time, such as the design life. In this case, durability will be defined as the probability that the structure will not degrade such that repair is required over the ship's design life, given the following information:

- Seaway wave loading is considered in the frequency domain, for a lifetime of operation.
- The structural scantlings used in the analysis are the original, as-built scantlings allowed to reduce over time according to corrosion or other time-based degradation mechanisms.
- System failure is defined as unacceptable degradation of the structure such that some level of repair is required. The failure threshold is determined as a result of an unacceptably high increase in the risk of serious system failure due to the degradation (for example, excessive corrosion or cracking). The failure definitions represent failures requiring some level of service.

- Structural degradation mechanisms are included for the life of the platform without inclusion of maintenance effects.

Operational Availability for ships is not treated explicitly in current practice, where it is assumed that an existing ship structure will be ready for a mission. Durability can be considered the probability that no failures occur in the life of the structure. Durability is the probability of failure requiring repair and makes up one portion of the availability measure, the other being repairability. Until a better availability measure for ship structure is available, the durability measure proposed here can be used, and is noted as Ao'.

The most likely durability failures will probably be due to wear-out mechanisms instead of overload mechanisms. The durability performance of ship structures is primarily concerned with fatigue damage and corrosion. Coatings are developed to guard against corrosion, but a corrosion margin is sometimes added to the ship structural scantlings in order to allow for the possibility of some corrosion to occur. This increase in scantlings brings with it a weight and cost penalty, and therefore must be kept at a minimum. This is affected by choices in metal types and coatings.

Ensuring the time to crack initiation is longer than the design life of the ship is an attempt to mitigate the risk of fatigue damage. Cumulative damage models are used to aggregate the damage caused by cyclic seaway loads and predict the number of cycles, or time at sea which would cause crack initiation. The time until crack initiation is the time to failure. The number of cycles in a specified period of time can be determined based upon a specified operational environment.

The mean-time-to-failure (MTTF) is considered to be a primary measure of the performance of an engineered system. The durability measure being proposed is the probability that the time-to-failure for the structure is greater than the platform design life. If the time-to-failure of the structure is modeled using a normal probability distribution, the MTTF would be the ship's design life, and the durability performance measure would be 50 percent. If a maintenance model were included, the inspection and repair cycles may be used to model the time-to-repair and allow development of an operational availability performance estimate. The durability of a critical ship structural detail with regard to fatigue degradation will be assessed in Section 6.4 to demonstrate the concept.

CHAPTER 3 METHODOLOGY

Currently, in ship design and life-cycle management, a formal, quantitative linkage does not exist between the ship structural performance and specific readiness and operational performance goals. The goal of this report is to build and demonstrate a methodology for the use of reliability-based, structural analysis technologies to support top-level, platform operational performance requirements for naval surface ship structure. Such a methodology will support the mitigation of technical and programmatic risks inherent in acquisition and life-cycle management of a ship structural system. The methodology proposed in this chapter will provide a linkage between top-level requirements and the ship structural design using structural reliability technologies. A case study will be provided later in the report to demonstrate important aspects of this application.

The evolving role of naval ship platform owners is one of management, with the contract and detailed designs being developed by industry. In commercial shipping, rules are developed by a classification society for use in determining whether the design is acceptable. The minimum required scantlings can be determined using equations and methods provided by the classification society rules (for example, ABS 1986). Classification rules have evolved such that they are being used to both develop a new design and determine acceptability of an existing design or structure. This usage may not achieve an optimal structural design, but it does ensure the final design is acceptable to regulatory bodies and also allows the platform to be insured against loss or damage.

Development of reliability-based, operational performance metrics is the basis of this report. The proposed performance metrics are much like those used in onboard ship systems. For onboard ship systems, acceptability is determined using the performance metrics: operational capability, operational dependability and operational availability. For the ship structure, the performance metrics proposed in this methodology are: structural operational capability (Co'), structural operational dependability (Do'), and structural operational durability (Ao'), and are defined in Section 2.4.

3.1 METHODOLOGY FOR PERFORMANCE ASSESSMENT

The methodology presented here assumes the availability of both a ship design and top-level ship structural performance requirements. The level of design detail will determine the depth and extent of the performance analysis. Assessment of early stages of the design will only provide a preliminary estimate of the ship structural performance. Top-level requirements (TLRs) should be articulated in such a way as to allow for uncertainties in the prediction process, level of design detail, expectations of the platform managers/owners, and historical levels of performance, both implied by the design code and expected by the owner/operator. This topic will be discussed further in Section 3.2. The approach used for the methodology is shown in Figure 1 and is as follows:

1. Given, a ship structural design and top-level requirements that define acceptable performance,
2. Determine set of failure modes appropriate for each performance metric;
3. Develop failure definitions and limit state equations appropriate to each FM/metric pairing;

4. Identify load prediction tools for each failure mode;
5. Identify strength prediction tools for each failure mode;
6. Develop input data to support reliability analysis of failure modes according to their metric relationship;
7. Conduct reliability analyses;
8. For each metric, determine the relationship between failure modes such that the failure probabilities can be used to determine the performance measure; and
9. Compare assessed performance metrics to top-level performance requirements to determine acceptability of the design.
    - If TLRs are met, then the design is considered acceptable.
    - If TLRs are not met, the design is considered unacceptable and thus rejected.

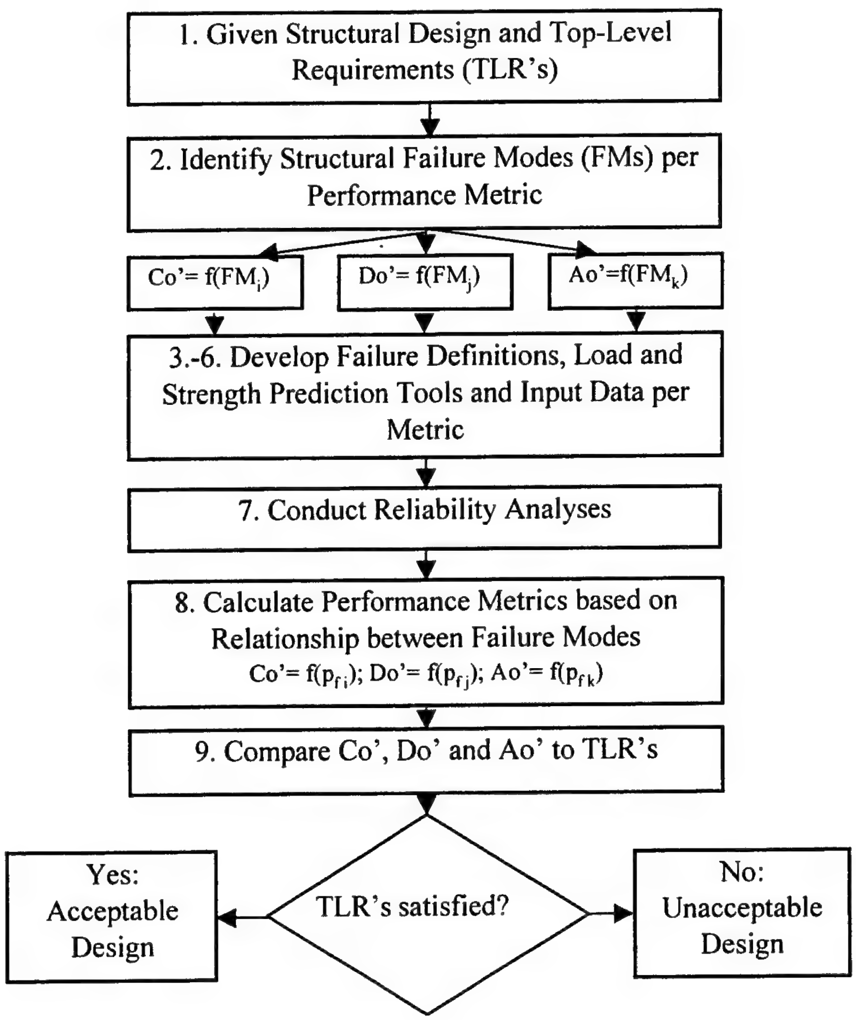

Figure 1. Methodology for Development and Use of Reliability-Based Performance Factors

3.1.1 Failure Mode Development

The platform structural system must be considered in the context of the platform system as a whole. The possible platform failure modes contingent on structural behavior can be identified using functional mapping of the structure to the total system. The functions served by the platform structure have to be determined at a range of levels from the highest system level to the component level. Operational failure of the platform is an event that restricts, degrades or prevents operation. Operational structural failure is the inability of the structure to perform the operational functions required by the platform. In simple terms, the function of the structure is to provide support and stiffness for dependent systems, and keep the water out. Structural failure modes are specific types of failure in the form of some unacceptable response by the structure to the operating environment that threatens or excessively degrades the integrity of the structure or a dependent system.

Each performance metric has certain conditions that determine which failure modes, or failure types are appropriate for inclusion. Failure modes that correspond to more than one metric will be considered in a way as to allow metrics to maintain some semblance of independence from each other. Loading and severity of the failure will play dominant roles in this determination. An example of this is the initiation of a fatigue crack. Durability performance requirements may dictate that the fatigue life of a ship structure be greater than the ship's design life to avoid the need for repairs. This requirement attempts to prevent crack initiation under operational loads over the ship's life. Detection of a crack may require repair depending on its severity and the timing of the discovery. If the crack is shorter than its critical crack length and is found while at sea, the crack may be stop-drilled to prevent further growth, and then monitored until a repair can be made dockside. If a crack propagates beyond its critical length it can result in a breach in the structural integrity, immediately degrading the mission effectiveness. Fractures of this type are controlled in the design process through material selection and structural configurations. Effective prevention of fracture improves the dependability performance of the platform.

The failure modes most associated with each performance measure can be developed given their significance with regard to the performance of interest. In general, an attempt should be made to consider all failure modes affecting performance; but, practically speaking, only those of greatest significance will need special focus for a particular performance measurement. Potential failure modes result in different levels of consequence. Those of most import to the owner/operator relate to operation of the platform. If a structural component collapses, the result could be either restricted or no operations due to safety concerns. If the structure system degrades due to corrosion to unacceptable levels, the platform may either be restricted in operation or taken offline for repairs, reducing the availability.

Taken together, the three proposed performance measures are to be used to manage failure modes traditionally considered in ship structural design, as well as those newly identified. Traditional ship structural failure modes will be discussed at length in Chapters 4 and 5.

An example of a failure mode that would be used for a dependability analysis is that of overall, hull girder collapse due to wave bending resulting from an extreme seaway environment. Passing waves induce bending moments which act on the ship hull structure. If the structural resistance is such that it cannot withstand the bending load, it will begin to fail locally. If the

magnitude of the bending moment increases and exceeds the cross-sectional, bending resistance, the cross-section will become unstable and could collapse and/or rupture.

3.1.2 Failure Definition Development

For a particular failure mode, the prediction of its probability of occurrence requires a limit state equation as outlined in the reliability discussion in Section 2.3. Limit state equations need a state variable which can provide a means of articulating the demand and resistance, and a threshold defining success or failure. The acceptability threshold is the failure definition for the failure mode, providing a transition value signifying the boundary between success and failure. A failure definition can be either crisp or vague. A crisp failure is one in which the transition from acceptable to unacceptable is clearly defined. Vague failure thresholds represent structural behavior for which the acceptable and unacceptable domains are not clearly demarcated. Failure thresholds must be developed for a given state variable such that they are both predictable with existing tools and meaningful to the greater system performance. The important concept of failure definitions for structural reliability assessment will be discussed at length in Chapter 4.

Capability and dependability performance address the probability of a failure occurring which would directly impact the mission effectiveness and survival of the platform during operation. Capability failure is defined as unacceptable decreases in structural integrity and support for dependent systems during the life of the platform. Dependability system failure is defined as unacceptable decreases in structural integrity and support for dependent systems during an extreme mission. The traditional failure definition types will be primarily crisp and traditional, reflecting rupture or other serious condition. Inclusion of dependent system failure modes for which the structure is the failure mechanism will introduce a failure definitions which may not be as concise, such as excessive deflection or vibration. For durability, system failure is defined as unacceptable degradation of the structure such that some level of repair is required. The failure threshold is determined according to there being an unacceptably high increase in the risk of serious system failure due to the degradation (for example, excessive corrosion or cracking). The durability performance metric addresses serviceability failures which would require repair and maintenance, and reflects a state of degradation, for which failure will be less well defined.

The failure definition for the bending collapse of a hull girder under wave loading can be considered to be the point at which the wave-induced bending moment, M_w, exceeds the maximum, predicted, resistance of the hull structural cross section, M_u. The state variable chosen for this failure mode is the bending moment, as both the strength and the load can be mapped into this domain. The limit state equation would become $g = M_u - M_w$. If $g < 0$ then failure is assumed to have occurred.

3.1.3 Load Prediction

Tools and techniques will need to be identified to provide load effect predictions for each limit state equation. The load is mapped into its effect in terms of the state variable chosen for the limit state equation. The predictive tools must generally be accepted in the structures community, and include modeling uncertainty characterizations. Each failure mode will have different needs with regard to predictive technologies. The specifics of load effect prediction and uncertainty for a ship under seaway loading will be discussed at length in Section 6.3.3.

A simple example of load effect prediction is the bending moment experienced by a ship hull due to seaway loading. Computer codes based on sea trials and towing basin testing are used to predict the bending moment acting on a ship with the hull idealized as a beam. The bending moment is made up of contributions due to stillwater, M_{SW}, wave, M_W, and dynamic, M_D, bending. Stillwater bending results from the interaction between the distributions of buoyancy forces with the ship's weight distribution while the ship is sitting still in calm water. Wave bending is a result of interaction of the passing wave and the ship. Slamming and whipping of the ship hull girder in more extreme wave environments cause dynamic bending. The overall bending forces affecting the hull girder can be considered to be the sum of these three contributors, with some consideration shown for the phasing of the load occurrence relative to each other. Conservatively the loads can be considered independent and given as $M_{SW} + M_W + M_D$.

3.1.4 Strength Prediction

Tools and techniques will need to be identified to provide strength, or resistance, predictions for each limit state equation. For structural resistance versus limitations introduced by dependent systems, the predictive tools must be generally accepted in the structures community, and include modeling uncertainty characterizations. Each failure mode will have different needs with regard to predictive technologies.

An example of strength prediction is the determination of the overall collapse resistance of the hull girder due to wave bending. Computer codes used for this calculation will be discussed in Section 6.3.2. Each code predicts the onset of failure across the ship section as each component collapses but still contributes to the overall bending resistance. The maximum bending resistance afforded by the cross-section is taken to be the ultimate bending moment supported by the hull girder, M_u.

3.1.5 Input Data for Reliability Analyses

The input data for each failure mode must be developed to support the conduct of a reliability analysis. The basis for the information will depend upon the type of performance being measured. Input data appropriate for each failure occurrence prediction will be based on assumptions developed for each metric (for example, the state of the structure and the types of loads).

Capability is defined as the probability that a ship structure performs successfully given the following load and strength information. Lifetime predictions are used for environmental and operational loads. Loads due to a single event such as combat loads can also be included. Structural scantlings are reduced to minimum values with no margins as may be included for consideration of corrosion or other time-based degradation mechanisms with no maintenance to be included. Uncertainty in the scantlings is included in the analysis. No structural degradation mechanisms are included, as the scantlings have been reduced to their minimum allowed values.

Lifetime environmental loads input information includes nominal stillwater loads, mission profile, operational profile, sea spectra, response amplitude operators and uncertainty characterizations of environmental load predictions. The load prediction tools to determine the wave bending moments for the example discussed in the previous sections use this information. Combat loads will be considered as a single, assumed event for which load data are supplied by the survivability experts for some given weapon event. The likelihood or uncertainty of this

event is not open to question by the structural analyst, but is prescribed beforehand as part of the capability TLR.

Dependability, or mission reliability, can be defined to be the probability that a ship structure performs successfully given that the structure is in an acceptable, functioning state at the start of the mission. Seaway wave loading is developed for a severe, short-term mission using the same types of information used in the lifetime load analysis for the capability prediction. The structural scantlings used in the dependability analysis are the original, as-built scantlings conservatively reduced by amounts in keeping with corrosion or other time-based degradation mechanisms, based on an assumed maintenance regimen. No maintenance is allowed during the mission. Structural degradation mechanisms are assumed to occur during the mission.

The durability performance metric will be defined as the probability that the structure will not degrade such that repair is required, for a lifetime load profile. The structural scantlings used in the analysis are the original, as-built scantlings allowed to reduce over time according to corrosion or other time-based degradation mechanisms, such as fatigue. Structural degradation mechanisms are included for the life of the mission without inclusion of maintenance effects. Durability is one part of the availability measure, allowing the estimation of mean-time-to-failure (MTTF) to be developed over the lifetime of the system. If a maintenance model were included, the inspection and repair cycles would affect the durability calculation such that the mean-time-to-repair (MTTR) may be estimated.

The input information for developing the resistance associated with all three performance metrics consists of material properties, fatigue behavior, structural member dimensions, or scantlings, and the overall structural dimensions. Material properties include yield strength, elastic modulus, Poisson's ratio, and ultimate strength. Fatigue behavior is the stress-to-load cycles relationship, expressed in the form of an S/N curve as used in the cumulative damage model. Structural member dimensions are variables such as plate thickness, stiffener height, stiffener flange breadth, web thickness, and flange thickness. The overall structural dimensions include frame spacing, compartment lengths, stiffener spacing, length-between-perpendiculars (LBP), and hull girder depth. A demonstration of their inclusion in the performance measurement will be provided in the case studies of Chapter 6.

3.1.6 Reliability Analyses

The information and tools generated in the preceding steps will be used to conduct a reliability analysis, to determine the likelihood of the failure mode occurring according to the conditions of the associated performance metric. Structural reliability theory was introduced in Section 2.3. The appropriate reliability methodology must be chosen for each failure mode analysis. The amount of information available, the significance and the complexity of the limit state variables for the failure mode will help determine the best reliability methodology. For some failure modes, the use of a Level II approximate method, like the Advanced Second Moment (ASM) analysis method, will be most appropriate. While for others a Level III approach such as Monte Carlo simulation will be the proper approach. The treatment of hull girder collapse for a dependability calculation at an early design stage might have to rely upon a rough prediction of the load and strength values, in which case the use of an approximate method is most appropriate.

3.1.7 Determine Design Acceptability

For each metric, the relationship between the failure modes probabilities must be determined such that the probabilities can be combined and compared to the performance TLR. This involves treating the set of failure modes associated with a particular metric as a system, accounting for the importance and functional relationship between the failure modes. For the purpose of introducing the performance metrics in this report, the combination of failure mode probabilities for a particular performance metric will be considered to be independent components in series, and the product of the calculated reliabilities will be considered representative of the structural system performance. This provides a lower bound on the system reliability.

The assessed performance metrics are then compared to the top-level performance requirements to determine acceptability of the design. If the TLRs are met, then the design is considered acceptable. If TLRs are not met, the design is considered unacceptable and thus rejected.

3.2 TOP-LEVEL REQUIREMENT DEFINITION

Though not new technologies, structural strength and load prediction remain inexact sciences. The complexities of the surface ship interaction with environmental loadings lead to approximate models with unknown accuracy. These resistance and load models have been used successfully in the past by attaching factors of safety, or safety margins, to ensure adequate performance. These margins have been developed from experience and may be considered the product of a dynamic calibration. Each new design has benefited from past experience. If the safety margin proved insufficient in the previous design, the next design may see a potentially substantial increase. If the safety margin used in the past proved successful (no failures), efforts to meet ship system performance requirements may begin to erode the margin to gain other system advantages.

The safety margins used in past designs are embodied in the design criteria and in the judgment of the structural designers. The resulting design contains two partial safety margins: the first is formalized in the code and the second is the result of engineering judgment. The current design criteria have been used to develop the minimum acceptable scantlings for surface ship structures. To ensure that the resulting design meets more qualitative considerations such as ruggedness and to address perceived insufficiencies in the code, structural designers may increase the scantlings above the minimum requirement. This increased conservatism is not always quantifiable, yet it plays an important role in ensuring the survival of US Navy surface ships. To include this engineering judgment in the design code, formal, rigorous metrics must be applied.

Reliability is the probabilistic assessment of the likelihood that a system will maintain adequate performance for a specified period of time under proposed operating conditions (Harr 1987). The assessment of the likelihood that a structure will fail requires realistic prediction of strength, loads, operational profile, and their inherent uncertainties. The use of probabilistic formalism in the characterization of these uncertainties allows the engineer to produce traceable calculations resulting in a measure considered to reflect the reliability of the structure. Ideally, the likelihood of system failure provides a platform-independent measure of the performance, which may be used to better understand the implications of changes to design parameters. For

example, decreasing structural scantlings to allow increases in the weight of other ship systems may reduce the performance or safety of the structure to unacceptable levels. A quantitative understanding of the effect of this change on the performance would allow the decision-makers to make more informed decisions. Deciding what constitutes acceptable and unacceptable levels of performance requires recognition of the consequences of failure. The joining of the probability and consequence of failure provides a measure called risk. Risk acceptability is not easily determined, as it requires communication and understanding to address technical, political and societal requirements.

Incorporation of reliability-based methods in performance-based acceptability criteria may be used to promote consistent and acceptable levels of risk in new designs. The prediction of absolute reliability levels for ship structures requires amounts of data currently unavailable to the analyst. Approximate reliability methods produce a reliability measure known as a safety index, which does not necessarily reflect the expected value of the failure likelihood, but is generally consistent in its predictions. Level II methods employ formalized approximations in place of complete probabilistic characterizations of the uncertainties. The uncertainties associated with strength and load prediction for ship structures are formally approximated and incorporated in the Level II approach. The resulting reliability prediction is "notional" as a result of these approximations and should not be considered absolute.

Development of appropriate and realistic top-level operational performance requirements must be based on the stated needs of the ship operator and owner, and the limitations and uncertainty of the performance prediction technologies. Each performance metric must be better understood as it would apply to the platform structural system in order to develop valid acceptability threshold values. Top-level requirements (TLRs) should be articulated in such a way as to allow for uncertainties in the prediction process, level of design detail, expectations of the platform managers/owners (such as the US Navy), and historical levels of performance. Past design practice should be assessed with current analysis processes to determine the historical levels of achieved performance as measured using current technology. This may be considered a manner of calibrating the analysis methodology prediction to experience.

Structural reliability predictions may be considered notional in that the analyses may not accurately represent reality due to simplifying assumptions and lack of knowledge. The resulting uncertainty leads to a mismatch between performance expectations and the ability to assess the performance of a structural system. Predicting structural reliability is based on the use of a physics-of-failure approach in the place of more traditional forms of reliability prediction, which is dominated by experimental testing. It is therefore important to develop reliability approach baselines for each failure mode as per the conditions of their associated operational performance metric.

Melchers (1995) provides a discussion of calibration to determine acceptable risk levels in hazardous industry. The use of calibration techniques has occurred in the structural engineering community to develop new risk-based design criteria of similar safety levels as past, design criteria. Melchers proposes the following outline.

1. Define a set of existing systems against which calibration will be performed.
2. Perform a "notional" level risk analysis for each system, using agreed data, generic simplifications of the systems, of their components and of the probability density functions for the relevant random variables, consistently across all systems. As much as

possible, consistency should apply across the systems in the set. It will be found that the "notional" probabilities for the various systems are not the same.

3. Identify any reasons for the inconsistent notional probability values, taking into account past experience, known deficiencies or lower than desirable performance characteristics. These should "explain" the variations in "notional" probabilities identified above. If not, it is reasonable to suppose that design assumptions at variance with accepted practice were made. If possible, these should be identified and reviewed. With this background and perhaps considering political realities, set an "acceptable" notional risk level. In so doing, the calculated "notional" risk levels might be weighted to account for severity of consequences associated with each of the systems being considered.

4. Analyze the new system using the same set of component and system simplifications and the same set of simplified random variable properties used in (2) above. If necessary adjust the design of the new system to meet the adopted "acceptable" notional risk level. Minor violations of the "acceptable" risk level target can be tolerated if particular features exist which have not been adequately considered in the risk assessment.

The approach may easily be adapted for the use of performance in place of risk measures. The operational performance of existing ship structures should be analyzed to develop a baseline understanding of historical levels of performance. The results should be considered in light of the Navy's operational experience with the same vessels to determine if the performance was adequate or in need of improvement. Final determination of target performance TLRs will have to be developed with the program managers for new ship acquisitions given the calibration results and future Fleet requirements and expectations.

The development of performance-based, design guidelines for the US Navy allows target component and system failure mode reliabilities to be incorporated into operational performance measures in the design process. The derivation of these target reliabilities is to be conducted through analysis of the reliability levels implicit in the current USN ships as embodied in their contract design drawings. This process may be called a calibration of the reliability levels in the new design criteria to the reliability levels inherent in the old criteria.

The change of the US Navy structural design criteria to a reliability and performance-based code requires determination of the appropriate performance levels of the structural system. As the levels of quantitative structural performance acceptable to the Navy community are unknown, and the predicted calculation is notional, the choice of acceptability thresholds for future ship structural designs must be based on past designs and design criteria.

As discussed previously, the safety margins used in past designs are a combination of margins implicit in the current code and additional margins added due to engineering judgment. If a calibration is conducted on example designs as produced through strict interpretation of the existing criteria, the designs produced by new performance-based guidelines would require the same subjective, scantling strengthening as the current criteria. To alleviate this concern, the design drawings produced for ships currently in service can be used for the calibration process. These designs are a result of the current US Navy design code requirements combined with the judgment of the design engineers. The performance-based, design guidelines being developed though calibration to these drawings would include the design engineer's past wisdom, lessening (but not removing) the requirement for additional (subjective) safety margins, but preventing

such judgment from being excessively eroded during trade-off discussions between the structural sub-system and the total ship system communities.

3.3 EXAMPLE APPLICATION

Design of a ship structural system to maintain its integrity over the life of the ship requires adequate strength to withstand all possible extreme and cyclic loads. Structural failure or excessive system performance degradation may occur in details, panels or the hull girder of the ship. The hull girder is the primary structure that is designed to resist the global demands posed by the ship's response to passing waves. The dependability performance expectations for the ship structural system require that the structure be able to survive a mission in an extreme, wave environment.

Current US Navy design criteria for the hull girder involves development of an assumed design bending moment using the static balance of the hull on a trochoidal wave for both hogging and sagging. This design bending moment is then used to obtain the *Mc/I* stress profile throughout a cross-section of the hull structure. The stresses at the extreme fibers are compared to design allowable stresses to judge acceptability of the cross-section design. These design stresses are also compared to stiffened and unstiffened panels' strengths to judge acceptability at the component level. The material-dependent, design allowable stresses have been developed along with the analysis technique described above to implicitly provide "adequate" safety margins for the design strength relative to the design bending stresses. This safety margin has typically been increased based on engineering judgment. The level of safety and reliability is left unstated, but has proven reasonably successful in past designs, although not completely. Past efforts to reduce the amount of structural weight have caused a reduction in hull structure material to the minimum required to ensure the design allowable stress is greater than the assumed design bending moment stress. This reduction has contributed to at-sea failures requiring costly repair and strengthening work, because actual bending moments have exceeded the assumed design bending moments. The traditional criteria have thus proven to be insufficient at ensuring adequate structural performance.

New, potentially nontraditional ship designs, such as the DD-21, may increase the risk that hull girder strength will prove inadequate over the life of the ship if new criteria and design tools are not developed. Changes from traditional ship designs include increased time at sea, nontraditional hull forms, and a much greater emphasis on weight reduction. These top-level, programmatic changes result in lower level, structural requirements unsupported by current design criteria assumptions. Current criteria assume a traditional hull form and construction, with a 30-year life, ten of which are at sea, and allow the structural designers some subjective leeway with regard to amount of material necessary to sustain hull girder integrity.

The operational requirements of a new ship include the expectation of the ship being at sea for a certain percentage of its lifetime. Traditionally, US Navy ships have been designed to last 30 years, with one third of their life at sea, or 10 years. Ship designs currently being considered are expected to last 40 years, with one half of their life at sea, or 20 years. The likelihood of encountering a damaging extreme load increases with the increase in time at sea. As a result, doubling the environmental exposure time can significantly impact the safety and performance of the ship structure if such changes are not formally considered.

New approaches have been developed for predicting the environmental load and hull girder strength and have been used to support analysis and design by the US Navy technical community. Direct use of these advanced methods for design requires creation of new acceptability criteria to provide an adequate safety margin. As the safety margin of current design criteria is implicit and dependent upon the analysis techniques, it is not easily transferred to a new design process.

Reliability-based performance measures provide a means of mitigating the risk associated with a change in the ship requirements. By accounting for improved predictive techniques and uncertainties in both the strength and load prediction, the likelihood of hull girder failure may be calculated for new ships and provide the basis for deciding acceptance.

A dependability performance, Top-Level Requirement (TLR) for a new ship could be that the hull girder must have a similar or better reliability against collapse, than past ships of a similar class, ensuring an acceptable level of performance as associated with this failure mode. This requirement can be addressed with structural reliability analysis. The following limit state equation may be used for hull girder reliability analysis.

$$B_u\, M_u \geq B_{SW}\, M_{SW} + B_{WD} M_{WD} \tag{3-1}$$

M_u	=	Ultimate bending capacity of ship hull girder.
B_u	=	Modeling bias and uncertainty (real/predicted) for ultimate bending capacity of ship hull girder prediction.
M_{SW}	=	Stillwater bending moment.
B_{SW}	=	Modeling bias and uncertainty (real/predicted) for stillwater bending moment nominal prediction.
M_{WD}	=	Combined wave-induced plus whipping, hull girder bending moment prediction, where $M_{WD} = M_W + M_D$.
B_{WD}	=	Modeling bias and uncertainty (real/predicted) for maximum lifetime bending load prediction.

In order to fulfill the TLR, past designs may be analyzed to determine their reliability against hull girder collapse. Information for ships similar to the proposed design class would be gathered in order to supply the needed input variable data to the above equation. This information includes probabilistically characterized, basic variable and modeling uncertainty for the strength and load predictions. An analysis is then conducted of the following equation to determine the probability of $g < 0$. This is the probability of failure, or p_f. The reliability is $1 - p_f$.

$$g = B_u\, M_u - B_{SW}\, M_{SW} - B_{WD} M_{WD} \tag{3-2}$$

Since past designs were not developed with reliability-based techniques, analysis of these designs will produce a range of reliabilities and therefore estimates of the dependability of the structure. Based upon this information, a decision must be made as to what constitutes the minimum, acceptable dependability performance.

The new design is then analyzed using the same process as developed for the analysis of past designs. The dependability of the new design is then compared to the minimum, acceptable dependability. If the dependability of the new design is greater than the required dependability, the design is acceptable.

CHAPTER 4 FAILURE DEFINITION FOR RELIABILITY ANALYSIS

Surface ships encounter numerous structural loads, for example, wave bending, whipping, slamming. The magnitudes and times of occurrence of these loads are highly uncertain. Some of these loads or combinations of loads are capable of severely damaging the ship's structure. Damage often results in a reduction or loss of structural integrity, or otherwise adversely affects ship system performance. Traditional design criteria use deterministic safety factors in equations to guard against the possibility of structural damage and ship system degradation and failure. Unfortunately these methods provide an undetermined level of safety and performance which experience has shown is not always adequate. Structural reliability methods allow the prediction of an occurrence likelihood for a particular event of interest (for example, structural failure), allowing the designer to limit the probability of undesirable events. Calculating the probability that a failure event will not occur provides a performance measure termed reliability.

The Society of Naval Architects and Marine Engineers (SNAME) publishes a book entitled the *Principles of Naval Architecture*. The chapter on the "Strength of Ships" (MacNaught 1967) describes the ship structure "as the material which provides the strength and stiffness to withstand all the loads which the ship may reasonably be expected to experience." Inability to fulfill this function, partially or completely, may constitute failure of the ship structural system.

The degree to which ship system performance deteriorates as a result of some structural response or load effect could range from insignificant to catastrophic. Such deterioration could impact the ship safety and survivability, and the ship's ability to continue its mission. The qualitative or quantitative effect of this deterioration will be subsequently referred to as the cost or consequence of the structural response. When the cost or consequence exceeds some accepted level, the structure has failed.

An example of structural failure is the permanent deformation of an unstiffened plate. Excessive permanent set may misalign some mechanical system rendering it inoperable; reduce the strength of a larger structural system beyond acceptable levels and endanger more critical systems; or be cosmetically unappealing. The consequence of the permanent deformation may also be an increase in the likelihood of greater system failures. The point at which the deformation level becomes unacceptable for the designer or surveyor is the onset of failure for the plate. The failure definition for the permanent set of unstiffened plating depends on the acceptability of the consequences of the permanent set. When the consequences are no longer acceptable, the plate has failed. A designer attempts to limit the likelihood of the plate experiencing such plastic deformation. A surveyor could identify such deformation as excessive and needing repair. Differences in the level of permanent set considered excessive by the designer and surveyor may exist due to modeling uncertainty and bias in the predictive tools used by the designer and the subjective nature of the surveyor's observations. This discussion is predicated on treatment of failure from the point of view of the designer, analyst, or decision-maker, where predictive tools are required, but can be extended to operational applications.

Traditionally, the designer applies his judgment to decide what structural behavior constitutes failure. This approach contains an implicit treatment of the consequence of the event, with the designer deciding acceptable and unacceptable behavior of the system in question such that he feels the design will be adequate. The threshold of design acceptability is molded into a limit state equation for use in decision-making. The limit state equation provides a threshold formulation where the system/component capability (resistance or strength) must be greater than

the demand (load) by some margin such that an acceptable structure results. Risk and performance based design approaches allow explicit, formal treatment of these safety margins that are traditionally matters of judgment.

There are many modes by which the hull of a ship can experience damage. Designers attempting to preclude these failure modes are highly dependent upon a physical prediction method for characterization of the response leading to failure. Due to the complexity of the ship structural system, the currently available physical prediction models are based on a component view, where the components are the hull girder, stiffened and unstiffened panels, and details. In both deterministic and classical reliability-based design and analysis, the structural responses for each component must have an associated limiting value, which defines the transition from survival to failure.

Arriving at an appropriate limiting value for a structural response requires the designer to decide what constitutes a failure event. Failure may or may not result from an easily identifiable change in state of the structure or response model. The failure definition depends on the structural response models, and the cost or consequence corresponding to the response. Each of these factors has an inherent uncertainty, which must be assessed prior to predicting the reliability of the structure.

This chapter provides methodologies for defining failure for reliability-based, marine structural design and analysis. A structural failure event is a change in state such that the structure no longer provides a required function (load-carrying or otherwise) or impacts some specified system performance to an unacceptable degree. Examples, discussion and taxonomies of failure events are explored for the different levels of the ship structural system (hull girder, stiffened panels and grillages, unstiffened panels and details) in this chapter and in Chapter 5. Changes to the traditional serviceability failure definitions are not possible without addressing the costs associated with the failures, either subjectively or objectively. The basis for the consideration of changes to traditional serviceability failure thresholds and implementation of new serviceability failure modes/criteria is provided in this report. The approach is predicated on treatment of failure from the point of view of the designer, analyst, or decision-maker, where predictive tools are required, but can be extended to operational applications.

In this Chapter, types of failure modes are described as reported in literature. These types are then expanded to establish classes of failure modes leading to a methodology for formulating the range of failure definitions. Failure definition examples are provided in Chapter 5 for the hull girder and structural components at both the ultimate and serviceability types of failure.

4.1 TYPES OF FAILURE MODES

Failure modes can be categorized as structural or non-structural failure. The structural failure modes may again be divided into ultimate and serviceability types of failure. Ultimate failure modes are representative of a strength limit, beyond which the component loses effectiveness or ability to carry additional load. Ultimate failure modes are quantified though the use of ultimate limit states (ULS). Serviceability failure modes are lower energy states and imply structural failure without overload, and which would occur prior to an ultimate failure. Serviceability failure modes are quantified though the use of serviceability limit states (SLS). Failures driven by non-structural system performance are classed as serviceability failure modes as they would not necessarily be in-phase with an ultimate failure, and are traditionally guarded

against with serviceability limit states. The two categories may be depicted using a load-shortening curve for a structural member undergoing progressive failure as shown in Figure 2.

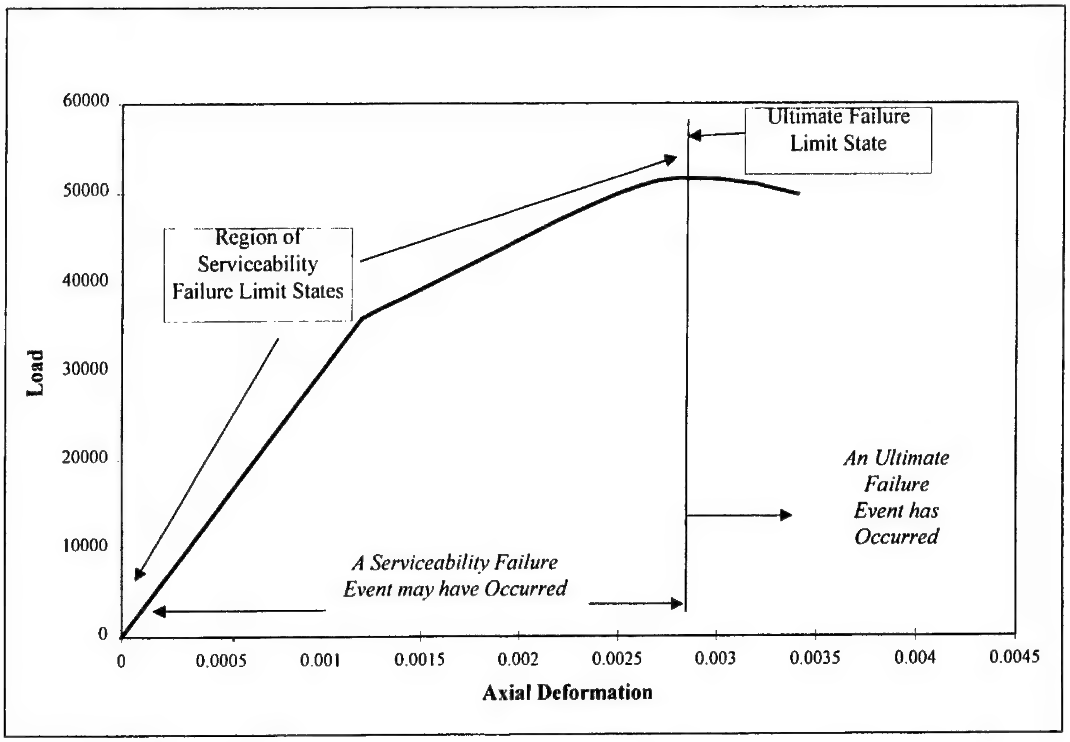

Figure 2. Types of Failure Modes vs. Structural Response

The lower energy region is associated with serviceability failure modes, while the peak of the curve represents the ultimate failure of the structural member. Failure modes corresponding to an ultimate strength limit are considered without uncertainty due to vagueness; either they can or cannot carry additional load and therefore are considered bivalent. Limit states for serviceability failures are prone to vagueness uncertainty as they are based on factors such as unacceptable degradation of structural system performance, parent system impacts, and tradition.

4.1.1 Failure Definitions from Literature

Report of the International Ship and Offshore Structures Congress (ISSC) Committee V.I (Planeix et al. 1982), in a description of failure modes and limit state design, states:

> "A structure in a limit state is a structure on the verge of going into an unwanted ("unsafe") situation with respect to some effects. One distinguishes ultimate limit states (ULS) relating to the structural safety of a design (trespassing the limit state results in collapse) and serviceability limit states (SLS) relating to the ability of a design to fulfill its functions… There is no limitation to the list of limit states of each category which may be adopted."

The report goes on to discuss the idea of "state parameters" which provide a quantified representation of the system/component status. Consistency between the demand and capability

state parameters allows identification of a failure event. Examples of demand and capability, state parameters for a jacket platform are shown in Table 2. The demand state parameter is the load, load effect or structural response. The capability state parameter is the ultimate strength or some other limiting value. The human acceleration limit is the amount of physical acceleration a person can withstand, due to platform motions, with no negative consequences.

Table 2. State Parameters for a Jacket Platform (Planeix et al. 1982)

Component	Demand	Capability
Bracing	Stress	Yield Strength
Bracing	Crack Length	Limit Crack
Underside of Platform	Wave Elevation	Air Gap
Quarters	Acceleration	Human Acceleration Limit

The categories and descriptions of ULS and SLS are consistent with those provided in Ellingwood et al. (1980), which presents a Load and Resistance Factor Design (LRFD) format for the design of buildings and other structures with respect to ultimate failure modes. The report defines two categories of limit states as:

> "Ultimate Limit States: are related to a structural collapse of part or all of the structure. Such a limit state should have a very low probability of occurrence, since it may lead to loss of life and major financial losses.
>
> Serviceability Limit States: are related to the disruption of the functional use of the structure and/or damage to or deterioration of the structure."

In Ship Structure Committee (SSC) report number SSC-392 (Mansour et al. 1996), examples of failure definitions for each structural level are presented for use with Level 2 methods of reliability analysis. This includes hull girder buckling, unstiffened plate yielding and buckling, stiffened plate buckling, and fatigue of details. The authors provide both ultimate and serviceability limit states. The serviceability failure modes depend on traditional limit states.

SSC-375 (Hughes et al. 1994) presents a discussion of structural failure modes and strength assessment models relevant to ship structural design. The focus of the work is the estimation of the modeling and random uncertainty associated with structural response models. The failure modes of principal members are listed along with appropriate response prediction models and the degree to which test data are available for validation. This list is shown in Table 3. The linking of structural system failure modes with structural response models is necessary for structural reliability assessment.

Table 3. Failure Modes and Response Models of Principal Structural Members (after Hughes et al. 1994)

Principal Member	Failure Modes	Failure Category	Prediction Model
Panel	Stiffener Flexure Collapse	ULS	Section 14.2 of Hughes (1988)
	Combined Buckling Collapse	ULS	Section 14.2 of Hughes (1988)
	Membrane Yield	ULS	Sections 13.2-13.4 of Hughes (1988)
	Stiffener Buckling Collapse	ULS	Section 12.5 of Hughes (1988)
	Stiffener Flange Tensile Yield	SLS	Beam Theory and Section 8.6 of Hughes (1988)
	Plate Tensile Yield	SLS	Beam Theory and Section 8.6 of Hughes (1988)
	Stiffener Flange Compressive Yield	SLS	Beam Theory and Section 8.6 of Hughes (1988)
	Plate Compressive Yield	SLS	Beam Theory and Section 8.6 of Hughes (1988)
	Plate Bending Yield	SLS	Section 9.1 - 9.2 of Hughes (1988)
	Local Plate Buckling	SLS	Section 12.6 of Hughes (1988)
	Excessive Permanent Set	SLS	Section 9.3 – 9.5 of Hughes (1988)
Beam	Tripping	ULS	Section 13.1 of Hughes (1988)
	Flexural-Torsional Buckling	ULS	Section 15.4 - 15.5 of Hughes (1988)
	Plastic Hinge Formation	ULS	Section 16.1 - 16.2 of Hughes (1988)
	Bending Yield	SLS	Beam Theory
	Beam Web Yield in Shear	SLS	Beam Theory
Grillage	Overall Buckling Collapse	ULS	Section 10.2, and 13.5 – 13.6 of Hughes (1988)
	Plastic Hinge Formation	ULS	Section 16.1 – 16.4 of Hughes (1988)

The 8th ISSC, "Lessons Learned from Failure and Damage of Ships" (Akita 1982) presents a discussion of structural damage and its frequency as found in commercial ships classed by Nippon Kaiji Kyokai between 1973 and 1978. The modes of structural damage to the ship's hull are dent, buckling, crack and wastage. The dominating failures were classified as:

1. Fatigue crack due to repeated stress (including vibration) in discontinuous structure;
2. Buckling due to high stress level or distortion;
3. Dent and buckling due to wave impact force;
4. Crack, dent and buckling due to corrosion;
5. Crack and deformation due to workmanship;
6. Crack due to improper material;

7. Crack and buckling due to improper cargo handling; and
8. Sea casualties such as collision, contact to quay, fire, explosion, and grounding due to improper operation.

The first and second classes occurred most frequently, and are also the most readily handled in the design of the structure. No explanation is provided as to what constitutes failure for each identified class, except that these were observed failures. The database is therefore a compilation of visible cracks and deformation ("buckling") that were deemed unacceptable by the surveyor, according to experience and inspection procedure. This listing is important as it provides failure modes needing further attention, but it is also important to emphasize the need for corresponding predictive tools and failure thresholds developed for reliability assessment analysis and reliability-based design. It is important to have a significant degree of correlation between the definitions of failure of the analyst and the surveyor. The traditional failure modes and predictive models described in SSC-375 and shown in Table 3, have limiting values defined as yielding, localized buckling or collapse which may be improved, modified or updated as a result of close integration with surveyor or owner observations.

Hawkins et al. (1971) provide the beginnings and guidelines for a structural failure database for ship structures. Surveys of ship damage reported to the U.S. Coast Guard, the Maritime Administration, and the Military Sealift Command were conducted in order to build a database by which to better understand the types of failures occurring in service, and assess the possibility of minimizing such failures. SSC-272 (Jordan and Cochran 1978) and SSC-294 (Jordan and Knight 1979) contain survey results for detail failures. These information sources can be used to address weaknesses in current design approaches as discussed above regarding Akita et al. (1982), but should not be used to predict rates of failure as the data populations are pooled without knowledge of all influencing factors.

The U.S. Coast Guard produced a classification of structural failures for surveyor use in Navigation and Vessel Inspection Circular No. 15-91 (U.S. Coast Guard 1991) that classifies failure for reporting procedures as follows:

Class 1 Structural Failure

A fracture that occurs during normal operating conditions (i.e., not as a result of a grounding, collision, allision, or other casualty damage), that is:

1. A fracture of the oil/watertight envelope that is visible and any length or a buckle that has either initiated in or has propagated into the oil/watertight envelope of the vessel; or
2. A fracture 10 feet or longer in length that has either initiated in or propagated into an internal strength member.

Class 2 Structural Failure

A fracture less than 10 feet in length or a buckle that has initiated in or propagated into an internal strength member during normal operating conditions.

Class 3 Structural Failure

A fracture or buckle that occurs under normal operating conditions that does not otherwise meet the definition of either a Class 1 or Class 2 structural failure.

Any failures reported under this system would constitute damage beyond the failure thresholds assigned for design in ultimate limit states for buckling, and fatigue limit states, providing qualitative evidence of events occurring outside the scope of the design assumptions. The design and owner communities should respond to this evidence and improve the information in the design assumptions for high-cost failures, and declare the low-cost failures as acceptable, leaving the design process unchanged. The distinction between high-and low-cost failure is up to the owners of the vessel.

Budd et al. (1981), in SSC-308, discuss the impact of hull structure flexibility on propulsion machinery. The authors cite the following reasons for the decreasing stiffness of hull girders:

1. Increased length;
2. Use of high-strengths steels;
3. Less stringent corrosion or wastage allowances;
4. Increased knowledge of structural response, encouraging less conservative designs;
5. Wider use of optimization techniques, in particular weight minimization, leading to smaller scantlings; and
6. Use of aluminum for superstructure construction.

SSC-308 describes the effects of decreasing structural stiffness can result in the following dynamic and static modes of failure:

<u>Dynamic</u>

1. Personnel discomfort from propeller induced or other steady-state vibration and noise;
2. Malfunction of electronic or mechanical equipment, including main shafting, bearing and gear failures from vibration or excessive displacement;
3. Unacceptable high-frequency stress peaks in primary structure due to impact loads such as slamming; and
4. Fatigue of primary hull structure from the steady-state vibratory response of springing.

<u>Static</u>

1. Excessive curvature causing premature structural instability in the primary hull structure;
2. Excessive deformation when loaded resulting in reduced payload capacity in the sagging condition, or lower bottom clearance;
3. Excessive hull deformation imposing structural loads on non-structural items such as joiner bulkheads, piping, propulsion shafting, hatch covers, etc.; and
4. Second-order effects introducing inaccuracies into many of the customary naval architecture calculations.

Each of the failure modes listed above (except the last) require the specification of acceptability limits on the structural response, or definitions of failure, to allow reliability analysis and ensure acceptable performance.

The effects of hull structure flexibility on the propulsion shafting (a portion of Static 3, above), is the focus of SSC-308 and is a serviceability failure type. This flexibility may impact the main propulsion machinery components by eclipsing the required operational tolerances. According to SSC-308, manufacturers of ship machinery assume a rigid foundation made of concrete, requiring the ship structural designer to create foundations accordingly. SSC-308 provides methodologies useful in evaluating the relationship between the structural design and machinery manufacturer's requirements, with failure defined as excessive hull girder flexibility. These methodologies are useful in performing trade-off studies in the preliminary design phase. The requirements of the manufacturers for different propulsion arrangements may be compared to the predicted structural response to determine the likelihood of propulsor failure due to hull girder flexibility.

4.1.2 Ultimate Failure Modes

Ultimate failure is the point at which a structural member is unable to continue to carry additional load as shown in Figure 2. Analytical approaches to assessing a structure either predict a response due to loading (for example, stress or displacement) or predict the ultimate strength (for example, collapse strength). To predict an ultimate failure, the designer may either choose a simple model which gives only the collapse or buckling strength, or a more complex model which shows the progression to ultimate collapse and beyond (post-buckling regime). The simpler model provides a very crisp threshold between survival and failure which is easily accommodated by structural reliability analysis techniques. The more complex model of the structural response portrays the progression from no damage to ultimate collapse, with the failure event threshold coinciding with the point of maximum load capacity. The modeling bias and uncertainty are required to achieve accurate results as is discussed in Hughes et al. (1994) and Hess et al. (1994).

For illustrative purposes, one may consider the Euler buckling equation as a simple model of an ultimate strength failure mode for a column due to elastic (bifurcation) buckling. Euler's equation is:

$$F_{CR}=\frac{\pi^2 EI}{L^2 A} \tag{4-1}$$

where F_{CR} = the critical buckling stress; E = Elastic (Young's) modulus; I = moment of inertia; L = column length; and A = cross-sectional area. If the axial load on the column divided by the cross sectional area is greater than F_{CR}, the limit state is exceeded and a failure event is considered to have occurred. The amount of disagreement between the predicted strength from Equation 4-1 and the actual failure stress of a slender column is the modeling bias. The variation of the strength prediction due to variability in E, I, L and A may be considered the random uncertainty.

Reliability analysis Levels 2 and 3 account for the ambiguous uncertainty surrounding the reliability prediction by treating the basic load and strength variables as random variables and can include measures of the strength and load, modeling bias and uncertainty. Ambiguity can also be accommodated in Level 1 reliability codes (for example, LRFD) if included in the derivation of the partial safety factors.

The complexity and redundancy found in the ship structural system forces the designer to make assumptions and simplifications. Strength predictions of the ship structural components

(for example, hull girder, stiffened panel, unstiffened panel, detail) are calculated using algorithms developed with empirical relations, which do not necessarily match the ship structural system being analyzed. Component tests rarely are able to capture the influence of the surrounding structure for the smaller components, forcing conservative boundary conditions to be assumed. To design components based on an ultimate strength formulation assumes that the connected structure does not influence the ultimate strength. This could lead to an overly conservative design. If consequences to the greater ship system and progressive damage are ignored, potentially high risk failure modes corresponding to lower energy (serviceability failure), pre-collapse structural response effects may be left out of the design formulation, resulting in a non-conservative design.

4.1.3 Serviceability Failure Modes

We may consider serviceability failure to be an event which increases the risk of ultimate failure to unacceptable levels, or degrades non-structural systems in an unacceptable manner. Knowledge about the functional roles that a component/system plays in its parent system (structural and non-structural) is embodied in serviceability failure modes. The availability of such knowledge is often lacking to the degree that it may be accurately used in design. A quantitative system model is required to completely understand the influence of the structural response, short of ultimate failure, on the parent system as a whole. As this system model and quantitative awareness are traditionally unavailable, approximations are required. Current serviceability limit states are based on experience, tradition, convenience or narrowly focused insight into the system role of a particular component. Figure 3 shows the range of approaches available for defining serviceability failure modes for reliability analysis.

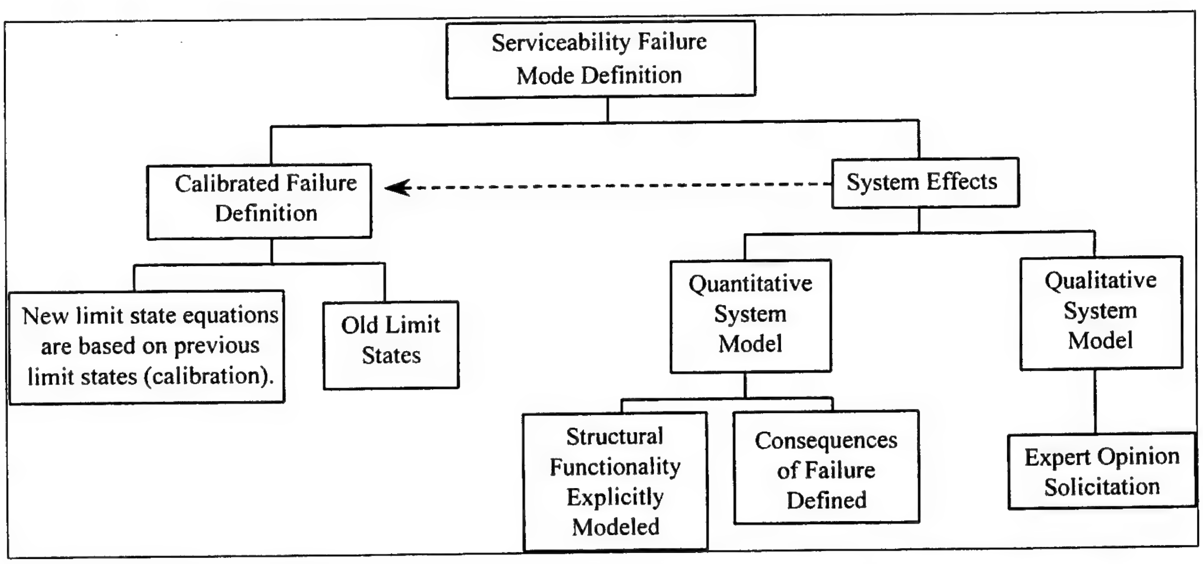

Figure 3. Approaches to Serviceability Failure Definition

Realistic serviceability limit states depend on the degree to which the greater or dependent system is degraded by the structural response. This system degradation must exceed some acceptable limit before being considered failure. The use of probabilistic risk analysis to

quantify the risk associated with the degradation scenario allows comparison to some governing risk criteria, which is the delineation between acceptable and unacceptable risk. The interdependence of the rational limit-state and the overall risk acceptability is discussed in Appleyard (1995) as risk negotiation. Risk negotiation is the communication and decision processes which the designer and the client use to arrive at a design with acceptable levels of risk. The comparison of the costs and benefits associated with the different risk levels helps decide acceptability. Therefore, a complex and difficult, but more progressive way of defining serviceability failure is to assess the increase in risk or decrease in performance, associated with the structural response, and choose the limit state as the response corresponding to the onset of unacceptable risk or performance. Without the means of conducting a full system risk assessment, the structural designer is left to develop approximate serviceability failure definitions such that work can progress.

Serviceability failure modes of the structural component are traditionally based on perceived component functions. Due to the lack of information and communication with the design of the parent system in which the structural component exists, the component's design must be based on tradition or engineering judgment. This information is embodied in the current written and unwritten design criteria, and in the minds and past decisions of the owners, operators, and inspectors for whom the idea of failure is multi-faceted and system-based.

A simple way to define a serviceability failure mode is to base new failure definitions upon those used in past designs. These limiting values, which correspond to the onset of a failure event, may be applied to a new structural response model. This allows adoption of a new model while attempting to maintain the implicitly accepted level of risk associated with the old model, essentially a calibration of the new response model to prior knowledge.

A traditional serviceability failure definition has been the onset of yield in the extreme fibers of the structural material. The structural response under consideration is the stress, which is then compared to the nominal yield strength of the structural material as derived from coupon testing. The idea of the loaded structure experiencing the onset of yield, or fraction thereof as in allowable stress, is an abstraction of convenience. This abstraction allows a limit to be placed on the allowable structural behavior such that higher energy, collapse mechanisms or fatigue cracking are prevented. Progressive damage resulting from consecutive near overloads (stresses higher than yield), may weaken the structure such that the collapse strength is markedly less than originally assumed, forcing the structure into the elasto-plastic domain. The unloaded structure, after such an overload, may not return to its original strength or geometry. Defining serviceability failure as the onset of inelastic behavior allows prevention of more uncertain, higher energy failures which have much higher associated consequences. The likelihood (probability of failure) deemed acceptable for the occurrence of yielding should be higher than the likelihood for collapse. It is important to note that the risk associated with yielding failure versus collapse failure may be the same or more if the acceptable probability of failure is chosen without consideration of the failure consequences. For example, if the likelihood of experiencing yield is 0.001 and the likelihood of experiencing collapse is 0.0001, and the consequences are 100 times greater for collapse than yield, the risk associated with collapse would be ten times greater than the risk from yield failure. Conversely, if the likelihood of yield failure is 0.01, then the risks are equivalent. For elastic buckling, where the critical stress is less than the yield strength, the probability of exceeding the yield strength can be set at a very low value to preclude buckling failure at an acceptable likelihood.

Traditional design equations developed to prevent structural serviceability failure are functions of the geometry, material properties and/or predicted design loads and load effects. Criswell (1979) discusses the uncertainty inherent in traditional, serviceability failure thresholds due to their dependence upon the predictive tools with which they are paired. The discussion is of deflection limit imposed on wood flooring, implicitly assuming a traditional predictive technique as compared to reality. Improvement or change in the structural response prediction requires a change in the failure definition, or limiting response, to reflect a different modeling bias and uncertainty. Probabilistic treatment of these uncertainties in a reliability framework allows the designer to map the historic failure threshold to a new value in line with the improved response model. The new failure threshold can be treated as uncertain with its own probabilistic characterization.

Probabilistic aggregation of (uncertain) limit states from different sources along with expert opinions allows the development of a probabilistically characterized failure definition. Treatment of the system dependencies on the component response, which are not clearly linked to the existing limit states, may be modeled using expert opinion. A probability distribution can be created which represents the likelihood of the failure threshold taking on a particular value of response. The probabilistically characterized failure threshold and structural response can be compared using reliability analysis to calculate the likelihood of failure.

Inclusion of new information into previous failure definitions (whether actual or calibrated expressions) may be achieved using probabilistic characterization of the limit states. Updating the limit state model is possible by using Bayesian probabilistic techniques for incorporating new knowledge and expert opinion into the existing model. This approach will be demonstrated in Section 6.2.

4.1.4 Non-Structural, System Failure Modes

Non-structural ship systems may experience failure where structural behavior is the root-cause. These failure modes should be considered in the design of the structure. The system performance impacts due to structural behavior (response) must be assessed and compared to acceptability criteria to declare the response event a failure. A greater amount of response can be allowed if the predicted response event provides a higher system performance, or lower risk level, than required by the governing criteria. Appleyard (1995) alludes to the process by which greater responses, and greater potential for damage, are allowed due to risk negotiation. Risk negotiation is the communication and decision processes which the designer and the client use to arrive at a design with acceptable levels of risk. The comparison of the costs and benefits associated with the different risk levels helps decide acceptability. This approach would provide the most rational framework in which to judge serviceability issues, but may also be implausible.

The lack of knowledge about the functional role of the structural component forces the designer to make an approximate model. This model may take the form of a functional mapping, taking the structural response and linking it to parent system behavior. Use of uncertainty measures and functions to allow for the lack of knowledge may provide a formalized method of approximation. Mapping of response to the parent or dependent system may be done using physical interaction models, or fuzzy approximations. This area may prove to be amenable to approaches based on possibilistic or fuzzy set theories.

The model proposed by Ayyub and Lai (1992) is useable in this context. This model uses a linear belief function to transition from complete success to complete failure. The response corresponding to the transition from complete survival to partial failure serves as the lower limit. The response corresponding to the transition from partial to complete failure serves as the upper limit. This approach is discussed further in Section 5.1. The transition model can represent an abstraction of the system's performance degradation in terms of the structural response, allowing the approximate model of the component's function to be considered in the design process. The Ayyub and Lai (1992) model is also discussed in broader terms in Alvi et al. (1992) and mentioned with respect to design methodology development in Ayyub et al. (1995).

As the process of approximating the system interactions may prove too burdensome, formal aggregation of experience and previous practice can allow treatment of non-structural serviceability failure at the structural component level.

4.2 METHODOLOGY TO FORMULATE FAILURE DEFINITIONS

4.2.1 The Damage Spectrum

The progression from success to failure for a structural system failure mode may be termed a damage spectrum. While some failures may be considered crisp events, others are more gradual. This damage spectrum may be partitioned to reflect different levels of failure. Crisp failures are those for which the community agrees upon the definition such as ultimate collapse or fracture. Non-crisp (vague) failure are those for which the community does not have an agreed upon definition. This could include elastic and plastic deformation, critical crack size or crack initiation, excessive vibration, or other unacceptable performance degradation.

A reliable system or component is one which performs its intended function under stated conditions for a specified period of time. Failure of the system or component is an inability to fulfill its function. Failure may also be considered an unacceptable lack of performance, where the threshold of acceptability is determined by formal or informal consideration of the associated risk. The identifiable ways in which a system or component may fail are considered failure modes. The occurrence of a failure mode is a failure event. Quantitative assessment of system/component failure likelihood requires the analyst/designer to define failure such that it is possible to calculate the probability of occurrence for each failure event. Defining a failure threshold requires understanding of the physical causes (structural response) responsible for each mode and explicitly considering the uncertainties found in both the failure mode definition and its associated physical cause(s).

4.2.2 Crisp Failure Definition

Classical reliability approaches treat the failure mode as a limiting point found in the physical behavior, delineating between success and failure, traditionally agreed upon by the community involved with the design process. This limiting point is mapped into a limit state equation born out of a model of the physical behavior and modified to reflect a crisp transition from success to failure. Analytical and numerical tools allow the designer to effectively model the structural response. These models are also able to incorporate ambiguous or objective uncertainty using simulation and other numerical techniques. Ambiguity is an uncertainty in the predictive models resulting from physical randomness of the model parameters, limited

information about these parameters, and simplifications, assumptions, or idealizations found in the predictive models themselves.

Current structural failure definitions, both for deterministic and reliability-based design, are based upon an assumed crisp transition from survival to failure, with only two, mutually exclusive events, complete survival and complete failure. This may be expressed as

$$U \rightarrow A = \{0, 1\} \tag{4-2}$$

where U = the universe of all possible outcomes; A = failure level scale; 0 = failure level of the event *complete survival*; 1 = failure level of the event *complete failure*. Figure 4 shows a crisp failure definition, δ_f, for some structural response δ. The threshold where a failure state begins is not necessarily based upon a structural collapse event, but may be a point beyond which structural or non-structural performance is affected (for example, permanent set of plates and beams). In this case, the limit state threshold is often chosen based on past experience and available predictive tools.

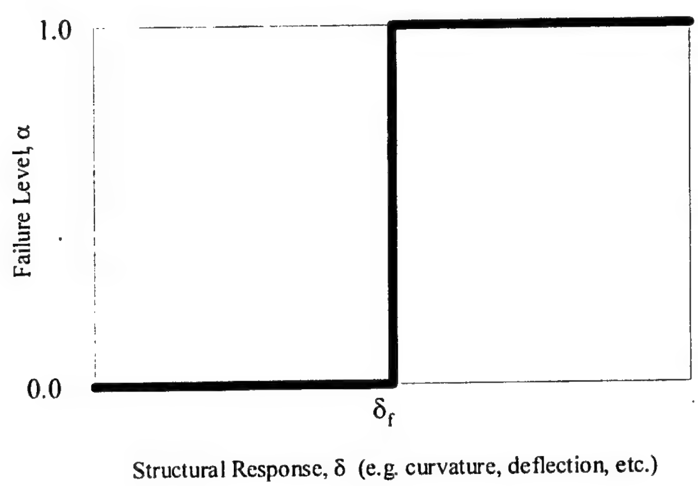

Figure 4. Crisp Failure Model (Ayyub and Lai 1992)

Convenience failure definitions may be used to address serviceability limit states such that the initiation of failure is deemed the failure point. Such a case may be found in crack initiation versus crack growth. If models are used to predict the formation of a crack, such as the cumulative damage model, the predictive tools will not lead the designer or analyst to a prediction of the size of the crack. The testing conducted will only predict the onset of damage. It is at this point that the event is classed as a failure, due to modeling limitations.

4.2.3 Vague Limit States

The choice of a failure threshold is highly important in determining the reliability of a system. Unfortunately in the case of structures, there is not necessarily an easily identifiable change in physical state that corresponds to the change in state judged to constitute failure by the engineer or operator. The inability to provide for the subjective view of failure is a weakness in traditional methods. This uncertainty in defining what constitutes failure may be considered subjective and is a result of vagueness. Vagueness is an uncertainty in the definition of certain parameters such as structural performance, quality, deterioration, and definitions of the

interrelations between the parameters of a system, particularly for complex systems such as a ship structure.

Structural system or component failure is rarely an all-or-nothing event. While the complete failure of a system may be easily defined, it is less likely to occur than a partial failure or unacceptable deterioration of system performance. A subjective index, failure level α, is introduced to represent the intermediate levels of damage. Equation 4-2 may be revised to reflect this new type of failure as:

$$U \rightarrow A = \{\alpha : \alpha \in [0, 1]\} \tag{4-3}$$

where U = the universe of all possible outcomes; A = failure level scale; $\alpha = 0$ is complete survival; $0 < \alpha < 1$ is partial failure; and $\alpha = 1$ is complete failure. Figure 5 shows the relationship between the failure level and the structural response δ. δ_l and δ_u represent the lower and upper bounds, respectively, of the partial failure zone. When δ is less than δ_l, α is zero, and the structure is considered to be in a state of complete survival. When δ is greater than δ_u, α is one, and the structure is considered to be in a state of complete failure. For values of δ between δ_l and δ_u, α takes values between 0 and 1 reflecting the level, or degree of failure. A failure level of 0.5 would denote a structure that is 50% failed in the mode of interest.

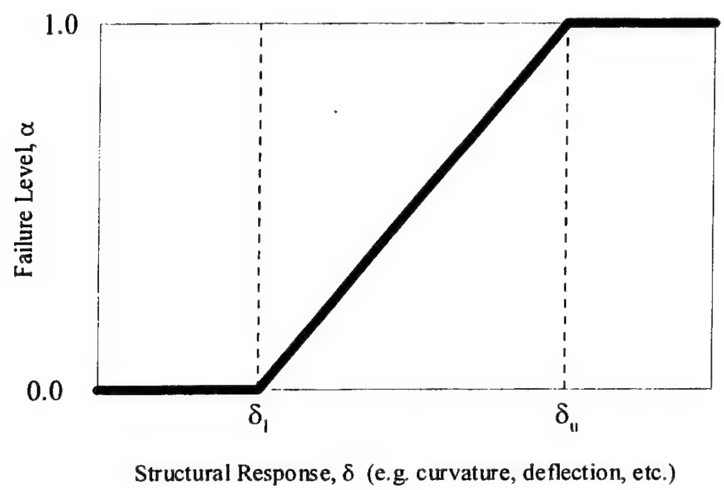

Figure 5. Vague Failure Model (Ayyub and Lai 1992).

Decisions based on the risk of failure and cost/benefit measures are highly dependent upon the underlying level of damage and the associated uncertainties. The acceptable levels of damage for one system may not be acceptable for another. Allowances for vagueness in the failure mode definition provide the designer with a procedure for incorporating subjective judgment into the design process.

Ayyub and Lai (1992) discuss the presence of failure levels from low serviceability to complete collapse. The paper suggests a treatment of the thresholds for each level as fuzzy boundaries whose properties are estimated through the use of expert testimony. Different weighting methods for aggregating expert opinion have been developed using both probabilistic (e.g., Modarres 1993) and fuzzy set (e.g., Hadipriona 1989) theories. Jovanovic et al. (1989) suggests an artificial intelligence approach and has developed a computer code toward this end.

It is possible that a more timely estimation of these boundaries between success and failure would result from a calibration based on the different design and acceptance criteria currently in use. This could be updated with improved knowledge or use of expert testimony.

Treatment of non-crisp structural failure modes has also been explored in the context of damage assessment of existing buildings by Yao (1980) and Dong et al. (1989). Shiraishi and Furuta (1982) bring attention to other types of failure such as mistakes, omissions, modeling errors and construction errors and incorporate them into the reliability analysis using fuzzy sets. Bourgund et al. (1989) discuss a damage index, which acknowledges the damage spectrum without introducing the use of fuzzy sets. The failure level, α, discussed in Ayyub and Lai (1989) and the damage index of Bourgund et al. (1989) are similar in that a value of zero represents success and unity represents complete failure. The use of a structure function, ϕ, in system analysis (see Høyland and Rausand 1994, or other system reliability references) is the reverse of the failure level, where success is unity and failure is zero, for use in Boolean analysis of system models. Ming-zhu and Guang-yuan (1989) propose a structure function and solution methodology which allows multiple states beyond the binary, success/fail approximation to failure, for analyzing structural systems.

The structural designer, or the creator of the design process, may choose probabilistic or possibilistic techniques to address the vagueness uncertainty accompanying the definition of structural serviceability failure or non-structural system performance failure. The primary focus of research into vague failure definitions in the structural design community appears to be aimed toward incorporation of fuzzy failure definitions into damage assessment and reliability calculations, with some efforts leading toward a blend of possibilistic (fuzzy) and probabilistic (Bayesian) approaches.

4.2.3.1 Possibilistic Vague Failure Model

The uncertainty surrounding whether a failure event did or did not occur can be characterized by treating the boundary between the two events as fuzzy. The use of fuzzy sets would assign a degree of belief regarding whether a failure event did or did not occur for each response.

Ayyub and Lai (1992) view the failure probability prediction as fuzzy, a methodology treated by Cai (1996) as fuzzy probist theory. Cai presents an extensive discussion of system reliability prediction with the use of possibility theory and fuzzy sets. A classification of the potential methods useable for reliability prediction are presented as follows (from Cai 1996):

- *Probist* Reliability Theory: The system failure behavior is fully characterized in the context of probability measures and assumes that the state of the system is binary with crisp delineation between success and failure.
- *Profust* Reliability Theory: The system failure behavior is fully characterized in the context of probability measures and assumes that success and failure are characterized by fuzzy states.
- *Posbist* Reliability Theory: The system failure behavior is fully characterized in the context of possibility measures and assumes that the state of the system is binary with crisp delineation between success and failure.

- *Posfust* Reliability Theory: The system failure behavior is fully characterized in the context of possibility measures and assumes that success and failure are characterized by fuzzy states.

Cai gives a very brief discussion of the utility of *posfust* theories for mechanical and structural reliability, but devotes the greater portion of the book to the use of *probist*, *profust* and *posbist* theories.

The work of Ayyub and Lai (1992) entitled "Structural Reliability Assessment with Ambiguity and Vagueness in Failure" presents a demonstration of a methodology for the treatment of the vagueness type of uncertainty as it relates to the definition of structural failure. This uncertainty is of the cognitive, subjective, or fuzzy type. The paper also uses probabilistic techniques to consider the ambiguity type of uncertainty, which may be considered non-cognitive, objective or random. Ayyub and Lai (1992) propose to incorporate the use of non-crisp failure modes into a structural reliability analysis using fuzzy sets to define the threshold of a failure event.

The methods used in Ayyub and Lai (1992) include the uncertainty in the failure mode definition in the calculated probability of failure, p_f. The probability of occurrence is calculated for different amounts of structural response (curvature: ϕ). Each curvature may have membership in one or more failure events. The curvatures and their associated failure likelihoods are then assembled according to the degree of membership in each event (α). Ayyub and Lai (1992) extract one value for the probability of failure for each performance event by finding the arithmetic and geometric averages of the probabilities of failure for the curvatures that are members of each performance event fuzzy set.

Ayyub and Lai (1992) explore the use of three failure models incorporating vagueness in their definition portraying the sensitivity of the probability of failure (reliability) to the definition of failure. The performance events are associated with a fuzzy index which is interpreted as either: 1) the level of damage (α=0 for complete survival, 0<α<1 to represent progressing degrees of failure and α=1 for complete failure); 2) a degree of belief that a performance event has occurred as a function of ϕ; 3) a degree of belief that "at least" a performance event has occurred as a function of ϕ. For the latter two, the authors partitioned the damage spectrum into six levels, from survival through increasingly damaging serviceability failure events, to ultimate failure. This gave results which are consistent with traditional engineering experience, with the likelihood of failure decreasing as the severity increased. Scientific and mathematical methods are presented which have allowed this analysis to be demonstrated. The application of this methodology to the hull girder under vertical, longitudinal bending is discussed in Section 6.3.

A reliability formulation by Holický (1998) proposes vague, performance (serviceability) failure to be defined as the condition where the action effect (response) exceeds some limiting performance requirement (limit-state). Holický (1998) goes on to discuss a fuzzy-probabilistic representation of the limit-state as it applies to floor vibration in offices. For each limit state, a range is proposed which defines the failure threshold. This fuzzy range is mapped into the probabilistic domain and is input into an optimization procedure based on cost. Each level of response has an accompanying consequence/cost. The optimum design corresponds to the lowest cost, where cost is the sum of the initial construction cost and the expected cost due to the predicted response distribution. This approach is a form of risk negotiation as discussed above.

4.2.3.2 Probabilistic Vague Failure Model

Bayesian analysis is an extension of classical probability theory, which gives the analyst a structured and mathematically rigorous approach to incorporating subjective knowledge into a probabilistic format. The axioms of probability are applicable and so the techniques join easily into the classical probability methods used in reliability assessment. The probability measure is considered a degree of belief founded in subjective knowledge, much like the approach used in fuzzy theory. Bayesian techniques are used in many different ways, including characterization of expert knowledge. The construction of a database of events considered failure in the past may be used to assess events in the future. Future events deemed to be failure (by experts), which do not prove similar to past events, might be used to update the database in a formalized manner using Bayesian techniques. This would be particularly appropriate for detail design, where databases have been in use for some time.

The lack of knowledge about the system functions of a structural component requires the designer to assign a degree of belief to a response level corresponding to whether or not the particular response represents serviceability failure for the component. Given a full, quantitative system model, the response failure threshold for the structural subsystem/component would be known. If a probability distribution is derived for the response failure threshold, this may be compared to the response probability distribution to arrive at a prediction of the likelihood of the failure threshold being exceeded. This approach has probabilistic characterizations of both the action effect (responses) and performance requirement in place of possibilistic (fuzzy) characterizations.

This method allows the failure likelihood to be calculated using the same techniques as would be used for classical structural reliability analysis, such as the Monte Carlo simulation and approximate methods (ASM). The response failure threshold distribution may be considered the resistance, and the predicted response distribution may be considered the load. In classical structural reliability, when the load exceeds the resistance, failure is considered to have occurred. For the framing of the serviceability failure likelihood discussed above, failure is considered to have occurred when the response exceeds the failure threshold.

Creation of the predicted response distribution depends on quantifying the uncertainty in the load and strength models and basic variables, as in classical structural reliability. The analytical method of combining the load and strength into a response measure is required, and not necessarily always available, nor accurate.

Approximation of the response failure threshold distribution may be done using a combination of traditional failure definitions and experience (expert opinion and historical failure identifications). Subjective (Bayesian) probabilistic methods are recommended for the development of the failure threshold distribution. The traditional failure definitions as used by different designers may be combined with expert opinion from ship structural inspectors to produce a probabilistic failure definition for immediate use. The probabilistic combination of failure thresholds for excessive permanent set of unstiffened plates is explored in Section 6.2.

The creation of a database of unacceptable structural behavior for which prediction tools exist would allow future analysis of the associated structural response measures, and probabilistic characterization. This response distribution may then be used to update the failure threshold distribution used in design to obtain a more meaningful failure definition. The existing reliability-based design process could immediately incorporate this improved knowledge.

4.2.3.3 Vague Failure Recognition and Classification

Prediction of the response of ship structural components or systems could require the use of nonlinear structural analysis. In such cases, failure definitions need to be expressed using deformations or resonant frequencies, rather than forces or stresses. Also, the recognition and proper classification of failures based on a structural response within the simulation process need to be performed based on deformations. The process of failure classification and recognition needs to be automated in order to facilitate its use in a simulation algorithm for structural reliability assessment. Figure 6 shows a procedure for an automated failure classification which can be implemented in a simulation algorithm for reliability assessment. The failure classification is based on matching a deformation or stress field with a record within a knowledge base of response and failure classes. In cases of no match, a list of approximate matches is provided, with assessed applicability factors. The user can then be prompted for any changes to the approximate matches and their applicability factors. In the case of poor matches, the user can have the option of activating the failure recognition algorithm shown in Figure 7 to establish a new record in the knowledge base. The adaptive or neural nature of this algorithm allows the updating of the knowledge base of responses and failure classes. The failure recognition and classification procedure shown in the figure evaluates the impact of the computed deformation or stress field on several systems of a ship. The impact assessment includes evaluating the remaining strength, stability, repair criticality, propulsion and power systems, combat systems, and hydrodynamic performance. The input of experts in ship performance is needed to make these evaluations using either numeric or linguistic measures. Then, the assessed impacts need to be aggregated and combined to obtain an overall failure recognition and classification within the established failure classes. The result of this process is then used to update the knowledge base.

A prototype computational methodology for reliability assessment of continuum structures using finite element analysis with instability failure modes is described in Ayyub (1996). Examples were used to illustrate and test the methodology. Geometric and material uncertainties were considered in the finite element model. A computer program was developed to implement this methodology by integrating uncertainty formulations to create a finite element input file, and to conduct the reliability assessment on a machine level. A commercial finite element package was used as a basis for the strength assessment in the presented procedure. A parametric study for stiffened panel strength was also carried out. The finite element model was based on the 8-node, doubly-curved shell element, which can provide the non-linear behavior prediction of the stiffened panel. The mesh was designed to ensure the convergence of eigenvalue estimates. Failure modes were predicted on the basis of elastic non-linear analysis using the finite element model.

Reliability assessment was performed using Monte Carlo simulation with variance reduction techniques that consisted of the conditional expectation method. According to Monte Carlo methods, the applied load was randomly generated, finite element analysis was used to predict the response of the structure under the generated loads in the form of a deformation field. A crude simulation procedure can be applied to compare the response with a specified failure definition, and failures can then be counted. By repeating the simulation procedure several times, the failure probability according the specified failure definition is estimated as the failure fraction of simulation repetitions. Alternatively, conditional expectation was used to estimate the

failure probability in each simulation cycle in this study, then the average failure probability and its statistical error were computed.

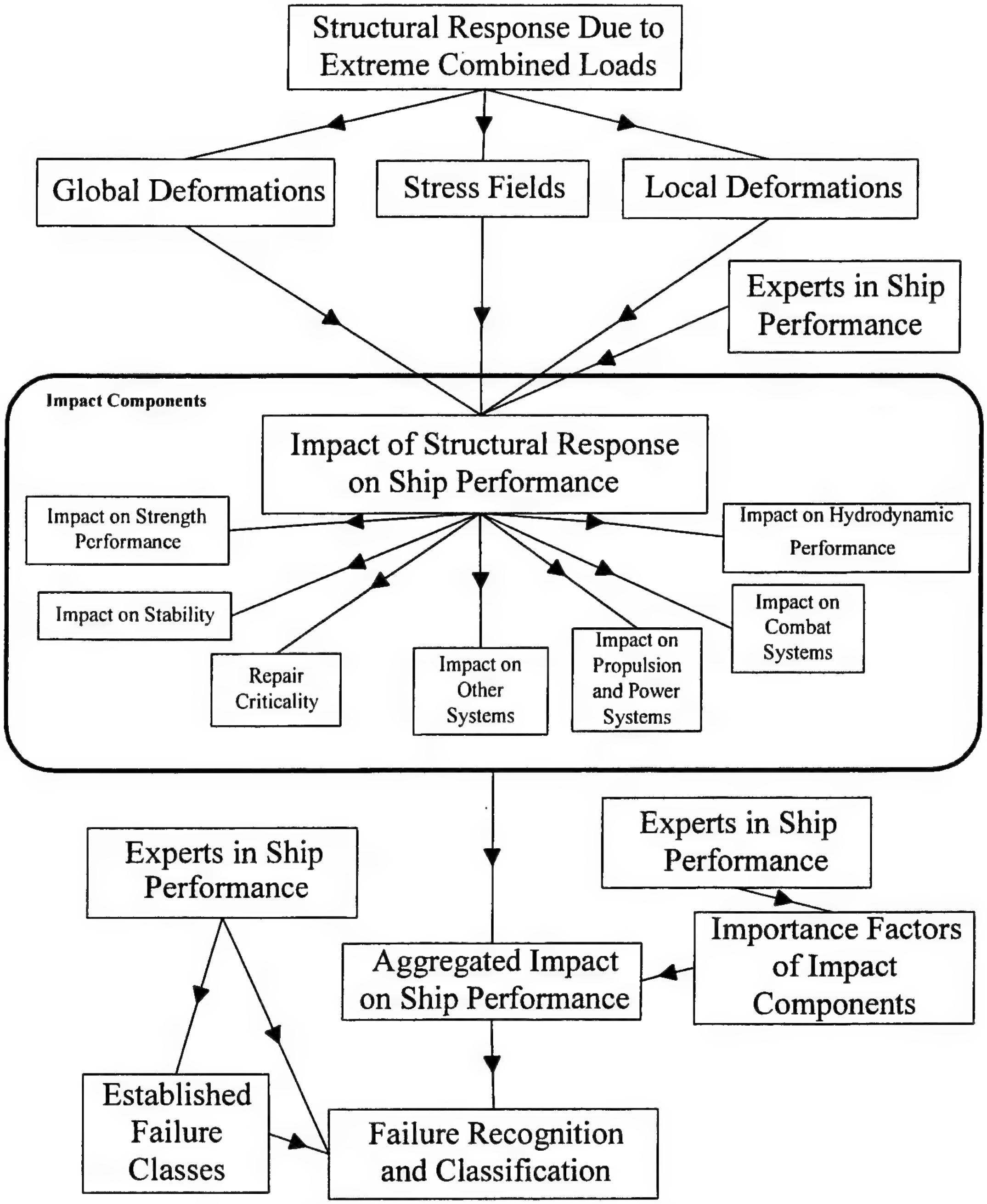

Figure 6. Failure Recognition and Classification Procedure (Ayyub et al. 1995; Ayyub 1996)

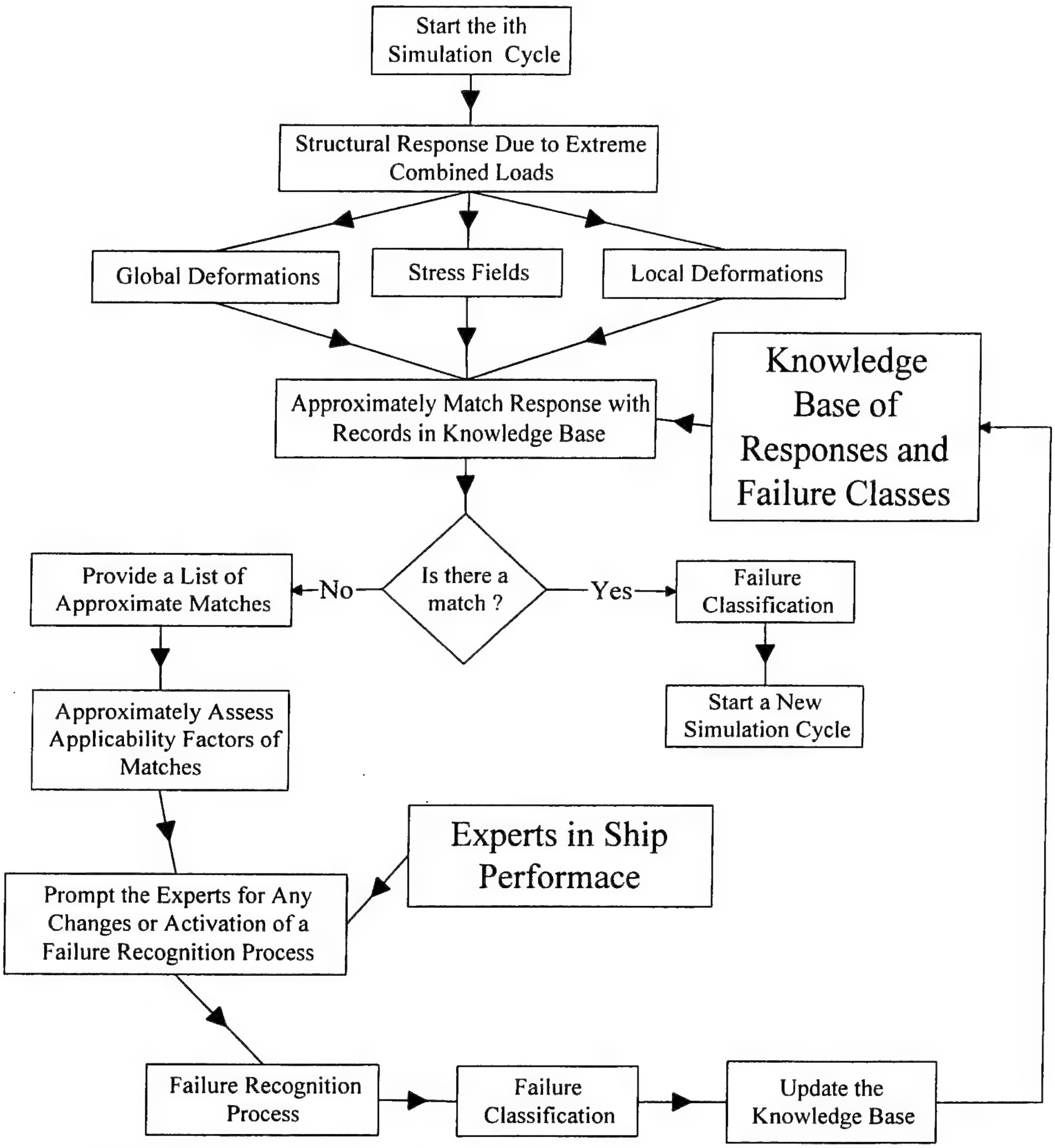

Figure 7. Failure Recognition Algorithm (Ayyub et al. 1995; Ayyub 1996)

4.3 FAILURE DEFINITION SUMMARY

Current design criteria use deterministic safety factors in design equations to guard against the possibility of structural damage and ship system degradation and failure. Unfortunately these methods provide an undetermined level of safety and performance which experience has shown is not always adequate. Traditionally, the designers apply their judgment to decide what structural behavior constitutes failure. This approach contains an implicit treatment of the consequence of the event, with the designers deciding acceptable and unacceptable behavior of

the system in question such that they feel the design will be adequate. The threshold of design acceptability is molded into a limit state equation for use in decision making. The limit state equation provides a threshold formulation where the system/component capability (strength) must be greater than the demand (load) by some margin such that an acceptable structure results. Reliability-based design approaches allow explicit, formal treatment of these safety margins which are traditionally matters of judgment. This formality is important in order to counter cost and other ship system demands which tend toward reduced structural safety levels.

Arriving at an appropriate limiting value for a structural response requires the designer to decide what behavior constitutes a failure event. Failure may or may not result from an easily identifiable change in state of the structure or response model. The failure definition depends on the state variable chosen to describe the failure, the structural capability and response models, and the cost or consequence corresponding to the structural behavior. Each of these factors has an inherent uncertainty, which must be assessed prior to predicting the reliability of the structure. The correlation between the limit state, state variable, and response model has a significant influence on the results of a reliability analysis. There are many modes by which the hull of a ship can experience damage. Designers attempting to preclude these failure modes are highly dependent upon a physical prediction method for characterization of the response leading to failure. Due to the complexity of the ship structural system, the currently available physical prediction models are based on a component view, where the components are the hull girder, stiffened and unstiffened panels, and details. In both deterministic and classical reliability-based design and analysis, the structural responses for each component must have an associated limiting value, which defines the transition from survival to failure.

The degree to which ship system performance deteriorates as a result of some structural response or load effect could range from insignificant to catastrophic. Such deterioration could impact the ship safety and survivability, and the ship's ability to continue its mission. The qualitative or quantitative effect of this deterioration can be considered the cost or consequence of the structural response. When the cost or consequence exceeds some acceptable level, the structure has failed.

Types of failure modes are described as reported in literature. These types are then expanded upon to establish classes of failure modes, leading to a methodology for formulating the range of failure definitions. A structural failure event is a change in state such that the structure no longer provides a required capability (load-carrying or otherwise) or impacts some specified system performance to an unacceptable degree. Changes to the traditional serviceability failure definitions are not possible without addressing the costs associated with the failures, either subjectively or objectively. The basis for the consideration of changes to traditional serviceability failure thresholds and implementation of new serviceability failure modes/criteria is discussed herein. The approach is predicated on treatment of failure from the point of view of the designer, analyst, or decision-maker, where predictive tools are required, but can be extended to operational applications.

CHAPTER 5 FAILURE MODES FOR SHIP STRUCTURES

The traditional levels of a surface ship structural system, each having sets of failure modes, are primary (hull girder), secondary (grillage and stiffened panel), and tertiary (unstiffened panel and local details). Current reliability-based design tools and methodologies for surface ship structures treat the different levels in a structural system as a set of components, each of which have their own particular modes of failure, or as a series system of independent components where the first component failure constitutes system failure. To be incorporated in the design methodologies currently in place or being developed, each level of the structural system must be addressed. Potential failure events must be identified and the structural response to the environment or loads, which lead to the failure event, must be characterized to include uncertainty, allowing application of these methods and enhancements to the design process.

5.1 HULL GIRDER

5.1.1 Discussion of Hull Girder Failure

As quoted in SSC-299 (Mansour and Thayamballi 1980), the 1967 International Ship Structures Congress (ISSC) defines failure of a hull girder as follows:

> "This occurs when a structure is damaged so badly that it can no longer fulfill its function. The loss of function may be gradual as in the case of lengthening fatigue crack or spreading plasticity, or sudden, when failure occurs through plastic instability or through propagation of a brittle crack. In all cases, the collapse load may be defined as the minimum load which will cause this loss of function."

SSC-299 and SSC-392 (Mansour et al. 1996) provide a taxonomy of possible failure modes for a hull girder under seaway loads, as well as techniques for calculating the hull girder strength under vertical bending, lateral bending and torsion, alone and combined. Fatigue and brittle fracture were excluded from the list. While brittle fracture of the hull is also possible and does occur, it is generally prevented by inspection, material choice and proper choice and treatment of structural details in accordance with fatigue considerations. The cited hull girder failure modes are as follows:

1. Failure due to yielding and plastic flow
    a. The plastic collapse moment
    b. The shakedown moment
    c. The initial yield moment
2. Failure due to instability and buckling
    a. Failure of the plating between stiffeners
    b. Panel failure mode (flexural buckling or tripping of longitudinals)
    c. Overall grillage failure mode

Failure due to instability and buckling is usually the governing mode. Multiple models of the ultimate strength of a hull girder under bending have been developed, but not in a reliability framework. SSC-299 presents detailed strength or capability models for each of the modes listed above. Failure is defined as the structural bending response in a seaway exceeding the calculated

resisting moment, capability or strength as defined in the list above. Each of these failure modes is assumed to be crisp with the limiting value being the result of direct calculation, though the capabilities and corresponding failure thresholds are not equivalent, representing unique failure definitions.

In a reliability-based context, SSC-398 (Mansour et al. 1997) describes primary failure as the occurrence of one of three failure modes for the hull girder: the fully plastic moment mode, the initial yield moment mode, and the instability collapse moment mode. Each failure mode defines failure as the exceedance of a specified hull girder resisting moment. The plastic moment can be considered an upper bound on the instability collapse moment. SSC-398 also includes a description of simplified methods for predicting the instability collapse moment mode as well as a description of the computer code ALPS/ISUM (Paik 1993). Each method presumes to predict the maximum load-carrying moment of the hull. A comparison of these methods to experimental and full-scale data is included and discussed. Multiple predictive models for the instability collapse moment are compared based on analysis of a 1/3-scale frigate in the 1994 ISSC Committee III.1 report (Jensen et al. 1994), showing the possible range of modeling uncertainty.

SSC-398 presents reliability analysis results for four ships in each of three different failure modes: primary, secondary and tertiary. Two failure definitions for primary failure of the hull girder are applied in the analysis. The first is when the seaway bending moment exceeds the initial yield moment, which is the product of the extreme fiber yield strength and the section modulus. The second is when the seaway loads exceed the ultimate collapse moment of the hull girder as calculated using ALPS/ISUM. The resulting ranges of safety indices (β) are shown in Table 4. The ratios of collapse over initial yield, safety indices and probabilities of failure, are shown in Table 5. The range of ratio values shows the inconsistency between these two definitions of failure. The simplicity of the initial yield moment failure definition makes it appealing for use in early design, but the scatter in the margin between the results of the two failure definitions signifies the need for added conservatism. This needed conservatism may invalidate the utility of highly simplified tools in reliability-based design. SSC-398 addresses this issue, concluding, "Designing a ship's structure based on yield strength criteria is unlikely to produce designs with a consistent level of reliability" (Mansour et al. 1997).

Table 4. Hull Girder Reliabilities from SSC-398 (Mansour et al. 1997)

Ship	Failure Mode	Short Term				Long Term			
		Sagging		Hogging		Sagging		Hogging	
		β	p_f	β	p_f	β	p_f	β	p_f
Cruiser 1	Yield	10.29	~ 0.0	10.45	~ 0.0	7.92	1.22×10^{-15}	7.40	6.86×10^{-14}
	Collapse	6.47	4.92×10^{-11}	6.75	7.43×10^{-12}	4.27	9.78×10^{-6}	4.09	2.16×10^{-5}
Cruiser 2	Yield	6.75	7.43×10^{-12}	7.77	4.00×10^{-15}	4.67	1.51×10^{-6}	4.54	2.82×10^{-6}
	Collapse	5.10	1.70×10^{-7}	6.22	2.50×10^{-10}	3.09	1.00×10^{-3}	3.18	7.36×10^{-4}
SL-7	Yield	6.26	1.93×10^{-10}	6.58	2.36×10^{-11}	4.20	1.34×10^{-5}	5.88	2.06×10^{-9}
	Collapse	5.83	2.78×10^{-9}	3.32	4.50×10^{-4}	3.84	6.15×10^{-5}	2.67	3.79×10^{-3}
Tanker	Yield	5.87	2.19×10^{-9}	5.01	2.73×10^{-7}	3.31	4.69×10^{-4}	4.03	2.81×10^{-5}
	Collapse	3.02	1.26×10^{-3}	2.82	2.40×10^{-3}	0.81	2.08×10^{-1}	2.03	2.14×10^{-2}

Table 5. Primary Failure Definition Ratios of Reliabilities from SSC-398 (Mansour et al. 1997)

Ship	Short Term				Long Term			
	Sagging		Hogging		Sagging		Hogging	
	$\frac{\beta_{IY}}{\beta_{Ult}}$	$\frac{p_{f\,IY}}{p_{f\,Ult}}$	$\frac{\beta_{IY}}{\beta_{Ult}}$	$\frac{p_{f\,IY}}{p_{f\,Ult}}$	$\frac{\beta_{IY}}{\beta_{Ult}}$	$\frac{p_{f\,IY}}{p_{f\,Ult}}$	$\frac{\beta_{IY}}{\beta_{Ult}}$	$\frac{p_{f\,IY}}{p_{f\,Ult}}$
Cruiser 1	0.63	-	0.65	-	0.54	8.0E+09	0.55	3.1E+08
Cruiser 2	0.76	2.3E+04	0.80	6.3E+04	0.66	6.6E+02	0.70	2.6E+02
SL-7	0.93	1.4E+01	0.50	1.9E+07	0.91	4.6E+00	0.45	1.8E+06
Tanker	0.51	5.8E+05	0.56	8.8E+03	0.24	4.4E+02	0.50	7.6E+02

SSC-392 (Mansour et al. 1996) provides an approximation of the ultimate (instability collapse) moment capacity of the hull girder using a reduced initial yield moment. This approach assumes a consistent margin between onset of extreme fiber yield and the occurrence

of buckling or instability failure. The margin is expressed as a knockdown factor c, which is based on material type. The knockdown factor may be calculated as the ratio of the instability collapse moment to the initial yield moment. The instability collapse moment is then calculated as the product of the knockdown factor, the extreme fiber yield strength and the section modulus. Failure is said to have occurred when the bending moment experienced due to waves, exceeds the maximum bending resistance of the hull girder. The knockdown factor approach outlined in SSC-392 shifts the initial yield strength prediction in a consistent manner, but would not significantly reduce the variation in the calculated reliabilities such that yield-based strength criteria may be used in design. The use of a knockdown factor to account for buckling-induced collapse of the hull girder will be explored in Section 6.3.

Should the margin between the initial yield moment and the ultimate bending moment be consistent, the desired reliability levels for hull girder collapse can be adjusted to allow for simplified capacity models without the use of a knockdown factor. As the occurrence of buckling precedes the onset of yield, a higher reliability can be associated with the initial yield moment (lower probability of failure) than the collapse moment due to buckling. The reliability levels for hull girder instability collapse failure can be chosen based upon more realistic considerations. The artificial target reliability levels chosen for the simplified failure definition and tools can be calibrated to assure some level of confidence in meeting the desired, realistic target reliability. The result allows simplified tools to be used in early design with adjusted target reliabilities set such that when more sophisticated tools are applied, the reliability targets assigned to realistic failure modes are met. The adjustment of target reliabilities to account for modeling simplifications, but calibrated against more complex analyses, can be used at any level of a structure to minimize complexity early in the design, but may not always be possible as shown in Table 5. It is important to emphasize the complete correlation between the target or assessed reliabilities, and the tools, information and especially the failure definitions used to develop them or to which they are applied.

5.1.2 Hull Girder Ultimate Strength

Hull girder ultimate strength is conventionally considered the maximum bending moment the hull girder is able to resist and can be considered a crisp event. Table 6 shows the two possible ultimate strength failure definitions limit values as yield strength and the maximum bending resistance. The dominant and most realistic failure mode is instability collapse. Failure is defined as the occurrence of an applied bending moment greater than the instability collapse moment. The other hull girder failure modes discussed above are a result of simplified modeling or should be considered in the context of hull girder serviceability failure or lower level, component failure.

Due to the seriousness of hull girder failure, the most realistic predictive tools available to the analyst or designer should be used. These include the incremental strain approaches such as ALPS/ISUM, ULTSTR, and others as discussed in Jensen et al. (1994). Lack of information at an early design stage may necessitate more simplified approaches, but the inaccuracies resulting from these models, particularly those based on yield strength formulations, must enforce greater conservatism on the part of the designer. Simple models more advanced than the yield strength-based models use similar amounts of information as computer codes such as ALSP/ISUM and ULTSTR, tending to reduce their utility to the designer. Failure modes such as the initial yield moment mode or the plastic moment mode are simplifications that may not provide consistent

measures of hull girder safety, and are probably not appropriate for use in reliability-based, design and analysis.

Table 6. Hull Girder Failure Modes

Failure Mode	Failure Type	State Variable	Limit Value	Reasons
Yield	Ultimate	Stress	Yield strength	Material failure
Collapse	Ultimate	Bending moment	Maximum bending resistance	Hull girder collapse and rupture
Onset of Damage	Serviceability	Curvature	Onset of nonlinearity in bending moment to curvature plot	Corresponds to onset of permanent structural damage
Vibration	Serviceability	Frequency	Natural frequency	Human comfort, equipment/machinery
Elastic Curvature	Serviceability	Curvature	Elastic curvature corresponding to operational shafting tolerance	Impact on non-structural items such as joiner bulkheads, piping, propulsion shafting, hatch covers, etc.
Plastic Curvature	Serviceability	Curvature	Plastic curvature corresponding to emergency shafting tolerance	Impact on non-structural items such as joiner bulkheads, piping, propulsion shafting, hatch covers, etc.

5.1.3 Hull Girder Serviceability Failure

As shown in Table 6, hull girder serviceability failure modes include excessive vibration, damage and deformation. Vibratory response due to insufficient stiffness can negatively impact equipment and machinery, as well as human comfort. The limiting value is most easily taken as the natural frequency, to guard against resonance. The onset of damage to stiffened and unstiffened panels in the hull girder is not acceptable for in-service conditions and is a serviceability failure mode. This limit state is defined by the onset of non-linearity in the plot of bending moment to curvature, or the bending moment resulting in the first component failure.

The ability to assess the hull girder bending load at the onset of damage, or first failure, as well as ultimate collapse, is afforded by the use of such computer codes as ALPS/ISUM and

ULTSTR. The point of initial failure can be predicted with these codes and compared to the ultimate bending resistance. The degree of separation of these loads is an indicator of the reserve strength and provides a measure of safety. For a description and exploration of the idea of reserve strength see Nikolaidis and Kapania (1990). Of course, the target reliability associated with first failure, must be less than that for ultimate collapse.

The range of possible intermediate failure thresholds between first failure and ultimate collapse due to hull girder bending is discussed and explored in Ayyub and Lai (1992). They provide a methodology for incorporating other intermediate failure modes into reliability-based design and analysis. The failure thresholds are portrayed using fuzzy membership functions, which would be developed using expert opinion. The focus of the study is the midship cross-section of a cruiser and its response to seaway bending loads. The computer program used to calculate the ultimate strength of the hull girder under primary loading is ULTSTR (Adamchak 1982). The manner in which ULTSTR assesses the ship ultimate strength is to apply a curvature, ϕ, to the hull girder, and evaluate the resisting moment provided by the cross-section of the hull. This method incorporates algorithms for progressive failure mechanisms at the component level, enabling the program to be used as a predictive tool for developing the cross-sectional structural system response.

For a particular hull girder cross section, the curvature of the hull girder is directly correlated with the structural bending resistance. When compared with the structural bending response due to seaway loads, it is possible to predict the probability that the seaway load exceeds the resisting moment and associated curvature. Figure 8 shows the relation between the curvature and the probability that the curvature is exceeded by seaway bending response, based on data reported in Ayyub and Lai (1992). For a chosen limiting value of curvature, such as could be prescribed by shafting requirements, a probability of failure can be determined from the plot.

Deformation or curvature of the hull girder resulting from response to bending loads can impact the effectiveness of ship systems dependent upon proper alignment such as the propulsor shaft. This failure mode and other stiffness related failure modes are discussed in SSC-308 (Budd et al. 1981) as described earlier. The experts involved with those systems would prescribe stiffness and deformation limits. Figure 8 shows the importance of choosing limiting values of structural response using risk negotiation or uncertain failure definitions as outlined in Ayyub and Lai (1992). If the system relying on the structure (i.e., shafting) can be designed to withstand greater amounts of curvature, the probability of exceedance decreases substantially beyond a curvature of 0.3×10^{-5}. Greater and more formal interaction between the structures community and the other ship system communities would provide the basis for better understanding of the performance needs of the ship, as impacted by the structure. The resulting failure thresholds should be provided by these non-structural communities in order to be included in the structural reliability assessment.

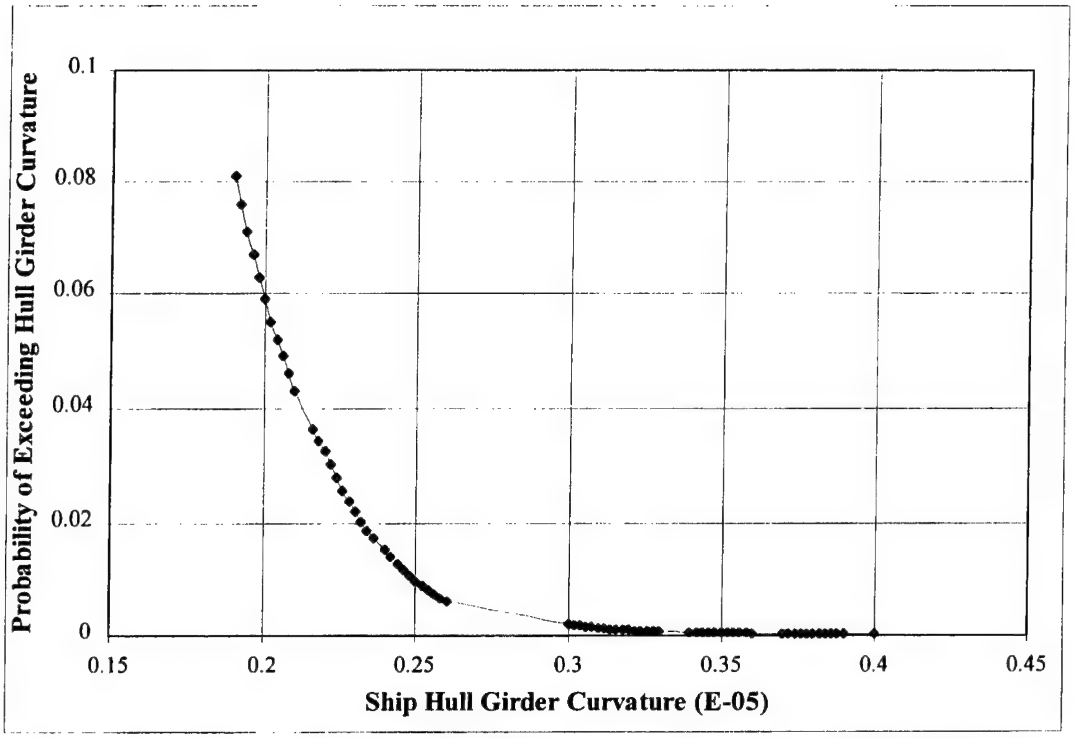

Figure 8. Probability of Exceeding Ship Hull Girder Curvature vs. Ship Hull Girder Curvature for Reported Damage Spectrum from Ayyub and Lai (1992)

5.2 STRUCTURAL COMPONENTS

Stiffened and unstiffened panels, beams and structural details are the components comprising a ship structural system. Much research and testing has gone into the development of models to predict component behavior over the life of the ship in both overload and fatigue. Failure definitions for grillages are in Table 7, stiffened panels in Table 8, unstiffened panels in Table 9, beams in Table 10 and details in Table 11. The strength and serviceability of plate panels will be addressed in the following section , followed by consideration of structural details under fatigue and fracture. An example of a vague failure definition for an unstiffened plate under lateral pressure is explored in Section 6.2.

Table 7. Grillage Failure Modes

Failure Mode	Failure Type	State Variable	Limit Value	Reasons
Plastic Hinge Formation	Ultimate	Stress	Plastic hinge formation stress	Reduction of strength
Overall Buckling	Ultimate	Stress	Buckling strength	Instability and reduction in load carrying ability
Vibration	Serviceability	Frequency	Natural frequency	Human comfort, equipment/machinery performance
Elastic Deformation	Serviceability	Displacement	Max. allowed elastic displacement	Equipment/machinery performance
Plastic Deformation	Serviceability	Displacement	Max. allowed plastic displacement	Equipment/machinery performance, strength reduction, stealth

Table 8. Stiffened Panel Failure Modes

Failure Mode	Failure Type	State Variable	Limit Value	Reasons
Tensile Yield of Flange	Ultimate	Stress	Yield strength	Material failure
Tensile Yield in Plate	Ultimate	Stress	Yield strength	Material failure
Compressive Yield of Flange	Ultimate	Stress	Yield strength	Material failure
Compressive Yield of Plate	Ultimate	Stress	Yield strength	Material failure
Compressive Collapse	Ultimate	Stress	Strength (Plate-induced, stiffener-induced, or combined)	Instability and reduction in load carrying ability
Stiffener Tripping	Ultimate	Stress	Strength	Instability and reduction in load carrying ability
Fracture, Crack Propagation	Ultimate	Crack length	Critical crack length	Prevention of fracture
Vibration	Serviceability	Frequency	Natural frequency	Human comfort, equipment/ machinery performance
Elastic Deformation	Serviceability	Displacement	Max. allowed elastic displacement	Equipment/ machinery performance
Plastic Deformation	Serviceability	Displacement	Max. allowed plastic displacement	Equipment/ machinery performance, strength reduction, stealth

Table 9. Unstiffened Panel Failure Modes

Failure Mode	Failure Type	State Variable	Limit Value	Reasons
Plate Bending Yield	Ultimate	Stress	Yield strength	Material failure
Membrane Yield	Ultimate	Stress	Yield strength	Material failure
Local Plate Buckling	Ultimate	Stress	Buckling strength	Strength reduction
Fracture, Crack Propagation	Ultimate	Crack length	Critical crack length	Prevention of fracture
Vibration	Serviceability	Frequency	Natural frequency	Human comfort, equipment/ machinery performance
Elastic Deformation	Serviceability	Displacement	Max. allowed elastic displacement	Equipment/ machinery performance
Plastic Deformation	Serviceability	Displacement	Max. allowed permanent set	Equipment/ machinery performance, strength reduction, stealth

Table 10. Beam Failure Modes

Failure Mode	Failure Type	State Variable	Limit Value	Reasons
Compressive Yield	Ultimate	Stress	Yield strength	Material failure
Tensile Yield	Ultimate	Stress	Yield strength	Material failure
Collapse	Ultimate	Stress	Strength	Instability and reduction in load carrying ability
Fracture, Crack Propagation	Ultimate	Crack length	Critical crack length	Prevention of fracture
Vibration	Serviceability	Frequency	Natural frequency	Human comfort, equipment/ machinery performance
Elastic Deformation	Serviceability	Displacement	Max. allowed elastic displacement	Equipment/ machinery performance
Plastic Deformation	Serviceability	Displacement	Max. allowed plastic displacement	Equipment/ machinery performance, strength reduction

5.2.1 Stiffened and Unstiffened Panels

Table 3 presents a listing of failure modes and capability models for stiffened and unstiffened panels as presented in SSC-375 (Hughes et al. 1994). A more general summary of failure definitions for grillages, stiffened and unstiffened panels are shown in Table 7,

Table 8 and Table 9, respectively. The model used to predict the limit value is not specified in these tables. Table 3 relates failure modes and limit values to a set of "first principles" prediction models providing limit values for the ultimate failure strength and local plate buckling failure modes. The term "first principles" refers to the use of derived, physics-based formulations representing the structural behavior without the use empirically-based factors to account for variations relative to experimental results. These failure thresholds are fairly well defined and represent an effective approach for reliability-based analysis and design. Certainly other strength models exist for these failure modes than those listed. The differences in these models are not a result of uncertainty in the failure definition, but of uncertainty in the models relative to actual structural behavior. The prediction models for the remaining serviceability failure modes provide a structural response, or load effect, to be compared with a limiting value of either the yield strength, or the permanent set of the unstiffened plate. The use of yield strength as a failure threshold is a traditional approach for localized material behavior, and is uncertain only with respect to the randomness found in the material given consistent and standardized testing regimes. Questions do remain with regard to whether the testing regime adequately mimics reality such as with strain rate effects. Issues regarding specification of a permanent set failure threshold, and the inherent uncertainties, are discussed in Section 6.2.

The stiffened panel represents the secondary structural level and is comprised of panels containing unidirectional stiffening members (such as a longitudinally stiffened sub-panel) and multidirectional stiffening members (considered a grillage). Appendix E of SSC-392 (Mansour et al. 1996) provides a discussion of failure modes and associated limit state equations for stiffened panels in the context of reliability design. Reliability-based consideration of the identified failure modes, such as those outlined in Table 3, depends upon the formulation of a complete set of limit state equations as demonstrated in SSC-392.

Unstiffened panels, or plates whose load-carrying capability is shared with adjoining structure are a fundamental building block of ship structures. This sharing can take the form of a plate-stiffener combination, as found in a longitudinally stiffened panel, or a hard corner configuration where multiple plates join as in a double bottom. Therefore, in primary loading, the unstiffened panel performs the role of a strength member until the decreasing stiffness of the plate allows load shedding to the usually stiffer, adjoining structure. In the case of uniaxial or biaxial stress, the plate undergoes elasto-plastic buckling. Numerous strength models have been formulated to allow calculation of the plate buckling strength. For reliability analysis, the plate's strength under in-plane, axial pressure, can be taken as the maximum resisting force, averaged across the loaded edge of the plate. Beyond this stress, the resistance of the plate declines, and the load is shed into adjoining structure.

In the case of lateral pressures, the plate deforms elastically and, ultimately, plastically in response to the load. The stiffness of the plate determines the amount of deflection due to lateral pressure, as well as the vibration response. Limitations on these responses must be specified for the designer, as they must be determined according to non-structural concerns. SSC-392 provides two limit states for a plate under lateral pressure. The first considers failure to be the

onset of yield at plate center due to lateral loads according to the Von Mises stress criterion. The second considers failure to be elastic/plastic deformation beyond some specified limit value. Neither of these failure modes corresponds to an ultimate failure event, and can be considered serviceability failure. Rupture of a plate is rarely considered explicitly in design, as the analytical formulations cannot predict this event. To arrive at a rational limiting value for the permanent set, subjective analysis of expert opinion should be coupled with quantifiable, objective analysis. An unstiffened plate is usually a component in a stiffened panel, which has a much greater load-carrying role. The consequences of plate deformation should be outlined quantitatively prior to defining failure for unstiffened panels.

The serviceability failure threshold may be mapped onto a two-dimensional space which includes structural response versus probability of exceedance. To include risk, a third dimension is needed to address consequence. Staying with the two dimensions, the threshold beyond which failure is assumed to occur may be viewed as a limiting value of the response function or failure likelihood. This approach is discussed for hull girder bending in Section 5.1.3.

5.2.2 Structural Details

Structural details are components whose primary function is in support of the structural system, by maintaining continuity between the larger structural members. The degree to which this performance is degraded is purely from the view of structural functionality. A secondary role is to ensure that the performance of equipment or machinery is not impinged. A summary of failure definitions for structural details is shown in Table 11. Should the detail be unable to fulfill its obligation to dependent structural or non-structural systems, it may be considered to have failed. The criteria by which the assessor would decide failure or non-failure may be either crisp or vague, depending on the function of the detail. Failure modes for details include yield, buckling, deformation and cracking. For ship structure, designing for low, local stresses to reduce fatigue damage usually prevents the types of overload that would lead to yielding, buckling, or permanent deformation. Reducing the likelihood of crack initiation due to cyclic loading is a primary consideration in detail design.

Table 11. Detail Failure Modes

Failure Mode	Failure Type	State Variable	Limit Value	Reasons
Material Yield	Ultimate	Stress	Yield strength	Reduction in strength
Buckling Collapse	Ultimate	Stress	Buckling strength	Reduction in strength
Crack Initiation	Serviceability	Fatigue damage	Cumulative damage limit	Prevention of fracture
Fracture, Crack Propagation	Ultimate	Crack length	Critical crack length	Prevention of fracture
Elastic Deformation	Serviceability	Displacement	Max. allowed elastic displacement	Equipment/ machinery performance
Plastic Deformation	Serviceability	Displacement	Max. allowed plastic displacement	Equipment/ machinery performance, strength reduction

For most purposes, the appearance of deformation (i.e., buckling) or a crack in a structural detail may be considered failure, as the point of maximum strength has most likely been violated

prior to the damage exposure. As a detail is designed to provide rigidity and continuity to the parent structure, the presence of a visible crack or deformation will alter its ability to perform as intended. For reliability-based design, the designer must be able to predict the likelihood of the detail cracking or buckling. Detail failure surveys can be found in SSC-220 (Hawkins et al. 1971), SSC-272 (Jordan and Cochran 1978), and SSC-294 (Jordan and Knight 1979), which present damage data from ship surveys.

Traditionally, the design of structural details is often based upon past experience and experimental testing. Due to the multi-dimensional nature of many structural details, analysis is not feasible without resorting to numerical methods, as closed form, analytical solutions are unavailable. The impracticality of applying computationally intense, numerical prediction methods to arrive at the probable structural response makes the use of physics-of-failure reliability methods unlikely at this structural member level. The traditional manner of guarding against cracking due to fatigue is based upon empirical data from cyclic testing to failure. Such tests provide the basis for a functional representation of the relationship between the stress, *S*, and the number of cycles, *N*, which resulted in "failure" of the test specimen. The resulting S/N curves may then be used to estimate the lifetime of the detail under normal operating conditions. Failure modes that result from overloading, including buckling and deformation, may be predicted by conducting experimental tests and analysis of past experience.

Convenience failure definitions may be used to address serviceability limit states such that the initiation of failure is deemed the failure point. Such a case may be found in crack initiation versus crack growth. If models are used to predict the formation of a crack, such as the cumulative damage model, the predictive tools will not lead the designer or analyst to a prediction of the size of the crack. The testing conducted will only predict the onset of damage. It is at this point that the event must be classed as a failure, due to modeling limitations. Planeix et al. (1982) discuss the need for a more clearly specified definition of failure in testing, giving examples of a 50% reduction in load carrying capacity and crack extension greater than 80-90% of a joint circumference. An approach for basing the design on test data is to assume that complete fracture of the specimen reflects crack initiation in the full-scale structure. This allows for scalability problems with fatigue testing but remains an approximation based on engineering knowledge.

5.3 FAILURE MODES SUMMARY

Failure definition examples are provided above for the hull girder and structural components for both the ultimate and serviceability types of failure. Summary tables of failure definitions are included. Hull girder failure definitions are shown in Table 6. Two strength failure modes are listed: yield and collapse. Three serviceability failure modes are shown for hull girder, grillage, stiffened panel, unstiffened panel and beam as exceedance of design limits placed on vibration, elastic curvature/deformation and plastic curvature/deformation. Grillage failure modes are listed in Table 7. Grillage strength failure definitions are plastic hinge formation and overall buckling. Stiffened panel failure definitions are listed in

Table 8. Stiffened panel strength failure definitions tensile and compressive yield, compressive collapse, stiffener tripping and fracture. Unstiffened panel failure definitions are listed in Table 9, with strength failure modes: bending and membrane yield, local plate buckling and fracture. Beam failure is shown in

Table 10 with strength failure modes of compressive or tensile yield, and compressive collapse. Detail failure modes are shown in Table 11. Detail strength failure is a result of material yield, buckling collapse or fracture. Serviceability failure of details can occur due to crack initiation, and elastic or plastic deformation.

Assigning failure definitions to the identified failure modes in design must be considered for each structure in question. Generalized failure definitions are limited to ultimate failure modes, where the collapse strength of a member is concerned. These types of failure are addressed to a large extent in current criteria and predictive formulations. Serviceability failure must be described based upon the associated consequences of the behavior using risk negotiation, expert testimony, or traditional failure thresholds.

Use of the proposed structural operational performance metrics requires identification of appropriate failure modes per metric. Generally speaking, the ultimate failure modes are appropriate for judging operational dependability. Operational durability is mostly driven by wear-out mechanisms for which failure is a serviceability issue. Serviceability failure modes appropriate for use in a durability measure are typified by some sort of permanent deflection, material loss, or structural weakening due to crack initiation, or onset of damage. Failure modes resulting from combat, accidental or other operational loads affect operational capability. Such failure can be considered either ultimate, as in the case of structural overload or rupture, or serviceability, as in the case of excessive vibration or deformation.

CHAPTER 6 CASE STUDIES

The following case studies will demonstrate the use and implications of the different operational performance metrics and their supporting reliability analysis methodologies. The notional destroyer shown in Figure 9 is the basis for the case studies. The hull is of conventional construction and design for a US Navy combatant, using longitudinally stiffened plating with transverse framing. The deckhouse is built from fiber reinforced plastic (FRP) skin, balsa core, sandwich panels.

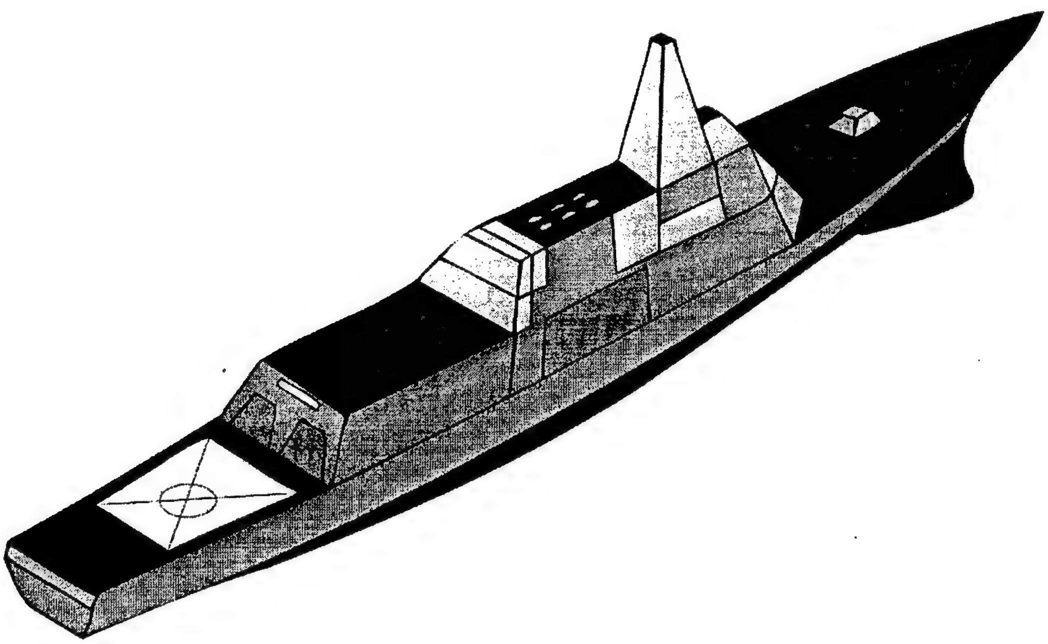

Figure 9. Notional Navy Destroyer

The first case study considers the TLR for the deckhouse to be capable of withstanding a blast, pressure load with some probability of survival. The second case study considers required limitations placed on the permanent deformation of side-shell plating on the hull. For both the first and second case studies, the TLRs are presented as "do not allow material rupture under a specified blast pressure" or "do not deform more than a certain specified amount under expected seaway loading." Both specifications are accompanied by probabilities of success that provide a measure of the structural capability performance in support of the TLRs.

The third case study addresses the dependability performance associated with hull girder collapse failure during a specified mission. The environmental load information is provided for the notional ship design for an extreme mission profile. The strength of the hull girder under vertical bending is presented using two methods. The first is a yield-based maximum bending resistance formulation, and the second uses the collapse bending moment. The dependability of the ship for the chosen extreme mission may be considered to be the product of the reliabilities

found for the specified failure mode along the ships length as the structure can be treated as a series system for one failure mode.

The objective of the fourth case study, discussed in Section 6.4, is to reformulate the conventional cumulative damage, fatigue life prediction methodology in order to produce a more useable measure of the probability of crack initiation in support of a durability performance metric. The conventional US Navy fatigue design procedure and a reliability-based procedure are presented for a critical detail on the notional destroyer. The prediction of durability performance of the notional combatant using a reliability-based, fatigue analysis methodology is conducted using extensions of existing technologies, revised to allow prediction of the probability of crack initiation during the design life of the notional combatant. The new reliability-based procedure provides a basis to judge the durability performance of the ship structure and give a probability that the ship structural availability is unity.

6.1 COMPOSITE SANDWICH PANEL CAPABILITY

The objective of this case study is to demonstrate the use of reliability-based performance measure of the capability requirement for a composite deckhouse panel under an air-blast, pressure load. Uncertainty in the loads, strength models, and failure definition are not considered in this demonstration but could be easily incorporated into the reliability methodology presented if available. The use of B-basis material property allowables is compared to the use of a reliability-based approach to provide information for decision-making based on performance, cost and weight considerations.

Traditional design approaches for structural systems have relied heavily on good engineering judgment and conservative assumptions in dealing with variations and uncertainty in material properties, loads, and performance criteria. Typically, uncertainty in data associated with structural design is approximated and considered in an informal manner by independent groups in the design process. For composite structures, the scatter in material properties is quantified by a group of experts as compounded knockdown factors on mean values of material properties. The degree of conservatism associated with these characteristic values is not explicitly treated, tracked or propagated in the design process. Likewise, uncertainty associated with loads, strength models, and performance criteria are also not considered in a formal, explicit manner, but are addressed by another group of experts in the form of maximum allowable stresses. These two, generally independent measures of uncertainty in design input parameters are passed to the designers where the combination of reduced material properties and maximum allowable stresses result in some unknown margin or factor of safety for the design in question.

6.1.1 Reliability Methodology

The reliability of a sandwich composite, deckhouse panel under blast loading has been chosen for this exploratory work. Reliability is the probabilistic assessment of the likelihood that a system will maintain adequate performance for a specified period of time under proposed operating conditions (Harr 1987). Reliability provides a quantitative measure of structural performance. Critchfield et al. (1994) discuss and give examples of sandwich composite topside structures undergoing air blast and shock testing in order to support dynamic load requirements on topside ship structural designs. A sandwich composite panel used in this study consists of two fiber reinforced plastic (FRP) skins separated by a core of balsa wood as seen in Figure 10. Tensile laminate failure and core shear failure are considered in the analysis, and are easily

expressed as limit state equations. Failure due to excessive deflection, buckling, and resonance with natural frequency are also possible but are not included in this analysis.

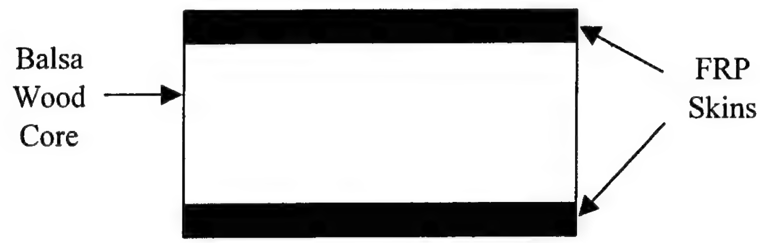

Figure 10. Sandwich Composite Panel Construction

6.1.2 Failure Modes and Limit States

For the design to be considered acceptable, the panel must be capable of surviving a prescribed, dynamic pressure load. For the chosen case of a dynamic pressure load, the governing types of failure are tensile-compressive laminate failure of the skins and shear failure of the core. These criteria are easily expressed in the form of a limit state equation. The generalized limit state equation for both failures can be expressed as

$$g = \frac{L}{R} \tag{6-1}$$

where $g > 1$ is failure. R is the structural resistance and L is the load effect. In particular, for failure of the skin, R is a function of the experimentally determined lamina strengths under hot/wet conditions. For failure of the core, R is a function of the experimentally determined shear strength. L represents stresses in the material induced by the applied pressure load and is a function of the material and geometric properties.

Lamina material properties are used as the basic variables. The laminate strengths and elastic constants are based on a set of experimentally determined values for a single unidirectional lamina. Classical Lamination Theory (CLT) is used to determine effective laminate behavior based on lamina parameters. CLT is discussed in textbooks such as Jones (1975). The lamina parameters, assuming plane stress behavior, are thickness, orientation of the fiber direction, elastic constants (E_{11}, E_{22}, G_{12}, ν_{12}), tensile (+) and compressive (-) strengths ($^{+}F_{11}$, $^{-}F_{11}$, $^{+}F_{22}$, $^{-}F_{22}$, F_{12}), and the variability associated with each of these inputs.

The failure of the laminate skin is considered to have occurred with the onset of failure in a single lamina. A quadratic stress-interactive limit state (Mayes 1999) is used to determine lamina failure. The mathematical form, under an assumption of plane stress, is given as:

$$g = \frac{f_{11}^2}{\left({}^{\pm}F_{11}\right)^2} + \frac{f_{22}^2}{\left({}^{\pm}F_{22}\right)^2} + \frac{f_{12}^2}{\left({}^{\pm}F_{12}\right)^2}, \tag{6-2}$$

where

F_{ij} = lamina strength ($i,j = 1,2$). Note the ± symbol indicates that either tensile or compressive strength values are to be used depending on stress state,

f_{ij} = lamina stress reference to the local (fiber) direction, and g > *1.0* is failure.

The primary failure mode of the core in a sandwich panel occurs by transverse shear. The limit state can be expressed as:

$$g = \max\left[\frac{f_{23}^2}{(F_{23})^2}, \frac{f_{13}^2}{(F_{13})^2}\right] \quad (6\text{-}3)$$

where $f_{23} = f_{13}$, and $g > 1.0$ is failure.

6.1.3 Uncertainty Sources

The treatment and propagation of uncertainties in material properties are considered in this analysis. The strength and load modeling uncertainty and uncertainty in the blast pressure are not considered. Uncertainty in the stress due to blast is considered as a function of the panel geometry and elastic modulii, with the blast pressure treated as deterministic. Table 12 lists the inputs for the reliability analysis. For the purposes of this demonstration, all basic variables are assumed normally distributed.

Table 12. Probabilistic Input to the Reliability-Based Panel Analyses

Lamina Random Variables		Core Random Variables
E_{11}	$^{\pm}F_{11}$	-
E_{22}	$^{\pm}F_{22}$	-
G_{12}	F_{12}	F_{12}
Thickness		Thickness

6.1.4 Panel Stress due to Blast Loading

The panel assessed in this study is 132 inches long and 96 inches wide. These dimensions are taken as non-varying. Panel skin and core thicknesses are the design parameters governing geometry for this analysis. Top and bottom skins were assumed to be identical. All fabrics were oriented with warps parallel to the panel's largest dimension. For demonstration purposes, the lamina orientation was assumed to vary according to a normally distributed alignment, with a mean of zero and standard deviation of 5 degrees. The probabilistic characterization of skin and core thicknesses is assumed normally distributed, with the nominal thickness to be the mean and a 5% coefficient of variation.

An equivalent, static pressure of 27 psi was applied to the panel, and was treated as non-varying. Modeling bias in the CLT model was neglected, but may be approximated by comparing it to other predictive methodologies or experimental results. Although uncertainty in

the pressure load was neglected, it could be easily incorporated into the reliability methodology presented if information is available.

6.1.5 Material Strength Prediction

Probabilistic characterizations of the variability in lamina properties were developed by analyzing data from tests conducted at NSWCCD, which are listed in Table 14 through Table 19. The balsa core shear strength was assumed to be normally distributed with a mean of 432 psi and 15% coefficient of variation. Elastic constants for the core were assumed to be non-varying (single value).

US Naval composite design practice traditionally uses knockdown factors to develop material allowable strengths. For the tensile failure of the skin, F is the laminate material, tensile strength. This strength is the result of adjusting the tested strength of the material for the environmental effects of temperature and moisture as follows:

$$F = \alpha_s \, \alpha_T \, \alpha_M \, F_U \tag{6-4}$$

where F_U is the ultimate tensile strength of the material; α_s is the knockdown factor used to account for statistical uncertainty; α_T is a knockdown factor to account for temperature effects; α_M is a knockdown factor to account for moisture effects. Typical values of knockdown factors used for marine composites are shown in Table 13. The ultimate tensile strength of the material is specified by the material's experts based upon their analyses of test data, and serves as an informal, lower bound to the possible values.

Table 13. Typical Knockdown Factors for Composite Structural Design

Type of Knockdown	Knockdown Factor
Statistical Variation, α_s	0.85
Temperature (190^{O}F), α_T	0.60
Temperature (125^{O}F), α_T	0.85
Moisture, α_M	0.75

6.1.6 Reliability Model

Monte Carlo simulation was used to predict the probability of failure of the composite panel under blast loading. The simulation computer code @RISK (Palisade Corporation 1997) was used with Microsoft Excel spreadsheet-based CLT and blast response prediction tools developed by researchers at NSWCCD. Monte Carlo simulation is a computer-based approach to allow generation of random values for the basic variables according to their probabilistic characterization, and calculating the resulting load and strength predictions. This process results in a sample population of paired load and strength observations. For each pairing the applicable

limit state is checked to assess the occurrence of failure as defined previously. The percentage of failures relative to the total number of load and strength pairings is the probability of failure for the specified failure mode.

For each simulation cycle, the reliability analysis process follows these steps:

1. @RISK generates random values for the basic (lamina) variables according to a prescribed probabilistic distribution model.
2. The CLT unit computes effective elastic constants for the panel, laminate skins.
3. The blast unit calculates maximum bending moments in the panel for the prescribed blast load.
4. The CLT unit determines whether the panel passes or fails according to stresses arising in individual lamina comprising each skin and shear stresses in the core.
5. @RISK records the maximum value resulting from the quadratic stress-interactive limit state *g*, using Equations 6-2 and 6-3.

This process results in a sample population of outputs from the quadratic failure criterion. The percentage of generated samples with a magnitude great than one is the probability of failure.

6.1.7 Material Data

Material allowables are defined in this report as a set of strength values. These values are used in design to provide some level of confidence that a structure will not fail under the influence of a given load. Typically, material allowables tend to be established around the lower bound of experimentally determined values. By adopting lower bound values, these allowables hopefully compensate for the variability inherent in manufacturing, test methodology, and a limited number of sampling points. These allowables have traditionally been specified using compounded knockdown factors to account for environmental degradation and statistical variability, and with the implied intent of being used in a traditional, deterministic design environment which uses some form of factor of safety. Currently there is no common or standard practice for the qualification of material properties in the composites community. However, the Federal Aviation Administration (FAA), National Aeronautics and Space Administration (NASA), Department of Energy (DOE) and Department of Defense (DoD) have been supporting development of Military Handbook 17 (DOD 1999) to provide a standard for composite material property qualification procedures. Statistical techniques, such as used in MIL-HDBK-17, have become commonly employed to characterize material variability and add accountability in establishing allowables or basis values for the distribution of a particular material property.

MIL-HDBK-17 methodology for determining material characteristic design values has not yet been fully adopted within the Navy composites community, but it has helped to guide plans for material testing. The final choice of material property allowable methodologies for the US Navy is undetermined at this time. MIL-HDBK-17 provides the methodology for the development of A- and B-basis characteristic values for the material properties such as tensile and shear strengths.

Materials experts conduct tests of the composite lamina and core to develop a sample population from which the lower bound of a confidence interval on a percentile is predicted. The material property value corresponding to the lower bound of the confidence interval is taken as the basis value for design purposes. A- and B-basis values are formally defined in MIL-HDBK-17, and have been developed to provide the designer with two methods of determining a material property value, or design allowable. When the procedures in MIL-HDBK-17 are used to develop the A- and B-basis values, there is a predetermined likelihood that the material property values occurring in the design will be less than the allowable. An A-basis value is the lower 95% confidence limit on the 1st percentile. The B-basis value is the lower 95% confidence limit on the 10th percentile.

A percentile is the value below which the stated percent of values will occur according to the assumed population probability density function. For example, the likelihood of an observation being greater than the 10th percentile is 90 percent and the likelihood of the 1st percentile being exceeded is 99 percent. Due to sampling variability for small sample sizes, each sample of observations will not accurately represent the parent population. As with other statistics such as the sample mean and sample variance, the sample percentile will probably not be exactly the same as the population percentile. To account for this uncertainty in the sample statistics, confidence limits are used.

A confidence limit provides bounds according to a particular sample of observations, between which the population statistic of interest will occur with some probability. This particular probability value has been denoted as the "confidence". Confidence levels are the degree to which the statement can be considered correct, and are given as a probability. Confidence limits can be two-sided, reflecting upper and lower values, or one-sided. MIL-HDBK-17 uses two-sided confidence limits. These values define a range for a given statistic in accordance with the prescribed confidence level. For two-sided, 95% confidence limits, the population statistic is predicted to be between the upper and lower limits with a probability of 95%, or greater than the lower limiting value with a probability of 97.5%.

This information is not readily understood nor incorporated into the design process by the designers. The filtering of the information such that only one value is passed between the materials experts and the structural designer leads the designer to include additional safety margins to the material property or design, such as factors of safety, leading to possibly excessive and detrimental conservatism. The use of combinations of the most conservative values for each strength basic variable guarantees an overly conservative result, as their joint likelihood is potentially nonexistent.

To obtain high confidence in B-Basis values, MIL-HDBK-17 recommends on the order of thirty specimens. This study uses sample data taken from laminates produced by five fabricators for NSWCCD and made from 18-oz. plain weave E-glass woven-roving and Dow's Derakane 510A vinylester resin. Six samples were taken from each laminate for experimental determination of material properties. The sample set for a single fabricator will be considered a "batch" in keeping with the terminology of MIL-HDBK-17. Statistical summaries of the material data under hot/wet conditions are presented in Table 14 through Table 18 for each batch. Table 19 shows the statistics if the data from batches 1-5 are considered to have come from the same population and are pooled together.

MIL-HDBK-17 recommends that an Anderson-Darling k-sample test be used to check for batch-to-batch variability when attempting to pool samples and characterize them using a single distribution function. Results from the Anderson-Darling test indicated severe batch-to-batch variability among the VARTM laminates, meaning the groups were drawn from different populations. Techniques found in MIL-HDBK-17 were used to develop B-basis values, including the Analysis of Variation (ANOVA) method. Different groupings of the 5 sample sets were considered to determine the proper B-basis values. B-basis design allowables are shown in Table 20.

Table 14. Material Elastic Constants and Strengths for Batch 1

Elastic Constants	Mean	Standard Deviation	COV
E_{11} (Msi)	4.3	0.22	5.0%
E_{22} (Msi)	3.87	0.33	8.4%
G_{12} (Msi)	0.48	0.07	14.8%
υ_{12}	0.14	0.02	17.7%
Strengths			
$^{+}F_{11}$ (ksi)	44.2	5.74	13.0%
$^{-}F_{11}$ (ksi)	50.73	4.44	8.8%
$^{+}F_{22}$ (ksi)	37.33	2.15	5.8%
$^{-}F_{22}$ (ksi)	42.86	4.38	10.2%
F_{12} (ksi)	6.64	0.55	10.0%

Table 15. Material Elastic Constants and Strengths for Batch 2

Elastic Constants	Mean	Standard Deviation	COV
E_{11} (Msi)	4.02	0.17	4.3%
E_{22} (Msi)	3.48	0.18	5.2%
G_{12} (Msi)	0.6	0.18	30.4%
υ_{12}	0.14	0.02	12.8%
Strengths			
$^{+}F_{11}$ (ksi)	54.65	2.52	4.6%
$^{-}F_{11}$ (ksi)	57.72	2.03	3.5%
$^{+}F_{22}$ (ksi)	46.28	1.61	3.5%
$^{-}F_{22}$ (ksi)	47.5	4.22	8.9%
F_{12} (ksi)	8.09	0.56	7.0%

Table 16. Material Elastic Constants and Strengths for Batch 3

Elastic Constants	Mean	Standard Deviation	COV
E_{11} (Msi)	4.3	0.24	5.5%
E_{22} (Msi)	3.68	0.28	7.7%
G_{12} (Msi)	0.43	0.04	9.5%
υ_{12}	0.13	0.03	20.6%
Strengths			
$^{+}F_{11}$ (ksi)	46.36	5.78	12.5%
$^{-}F_{11}$ (ksi)	40.83	8.12	19.9%
$^{+}F_{22}$ (ksi)	40.42	2.7	6.7%
$^{-}F_{22}$ (ksi)	41.56	3.22	7.8%
F_{12} (ksi)	5.97	0.35	5.9%

Table 17. Material Elastic Constants and Strengths for Batch 4

Elastic Constants	Mean	Standard Deviation	COV
E_{11} (Msi)	4.28	0.17	3.9%
E_{22} (Msi)	4.12	0.44	10.7%
G_{12} (Msi)	0.46	0.0634	13.9%
υ_{12}	0.16	0.03	21.7%
Strengths			
$^{+}F_{11}$ (ksi)	60.47	2.27	3.8%
$^{-}F_{11}$ (ksi)	45.32	11.87	26.2%
$^{+}F_{22}$ (ksi)	44.24	2.1	4.8%
$^{-}F_{22}$ (ksi)	48.15	7.16	14.9%
F_{12} (ksi)	9.41	0.29	3.1%

Table 18. Material Elastic Constants and Strengths for Batch 5

Elastic Constants	Mean	Standard Deviation	COV
E_{11} (Msi)	3.92	0.44	11.2%
E_{22} (Msi)	3.59	0.17	4.8%
G_{12} (Msi)	0.52	0.07	13.7%
υ_{12}	0.14	0.04	27.0%
Strengths			
$^{+}F_{11}$ (ksi)	51.1	3.56	7.0%
$^{-}F_{11}$ (ksi)	46.33	8.38	18.1%
$^{+}F_{22}$ (ksi)	42.2	2.91	6.9%
$^{-}F_{22}$ (ksi)	39.71	3.16	8.0%
F_{12} (ksi)	6.49	0.49	7.5%

Table 19. Material Elastic Constants and Strengths for All Batches Combined

Elastic Constants	Mean	Standard Deviation	COV
E_{11} (Msi)	3.890	0.287	7.4%
E_{22} (Msi)	3.747	0.359	9.6%
G_{12} (Msi)	0.4776	0.101	21.1%
υ_{12}	0.1320	0.029	21.8%
Strengths			
$^{+}F_{11}$ (ksi)	51.35	7.126	13.9%
$^{-}F_{11}$ (ksi)	-44.95	9.396	20.9%
$^{+}F_{22}$ (ksi)	42.09	3.816	9.1%
$^{-}F_{22}$ (ksi)	-43.95	5.489	12.5%
F_{12} (ksi)	7.088	1.211	17.1%

Table 20. ANOVA, Mean and B-basis Values

Elastic Constants	Mean	B-Basis Value	Batches
E_{11} (Msi)	3.76	2.97	1,2,3,5
E_{22} (Msi)	3.27	2.38	1,2,3,5
G_{12} (Msi)	0.57	0.19	1,2,3,4,5
υ_{12}	-	-	
Strengths			
$^{+}F_{11}$ (ksi)	49.08	29.33	1,2,3,5
$^{-}F_{11}$ (ksi)	-47.11	-29.55	1,3,4,5
$^{+}F_{22}$ (ksi)	41.56	26.08	1,2,3,5
$^{-}F_{22}$ (ksi)	-42.90	-32.78	1,2,4,5
F_{12} (ksi)	7.01	4.16	1,2,3,5

6.1.8 Reliability Analysis Results

The Monte Carlo simulations exercised the Latin Hypercube sampling option of @RISK, with a random number generator seed of 770. Convergence of the limit state output statistics

was achieved within 1000 iterations, as measured by less than a 1.5% change in percentile, mean, and standard deviation values. Failure probabilities for each batch and a variety of panel designs are shown in Table 21 through Table 26. The failure probabilities shown in Table 26 are the result of using material property data from all batches combined as one population. The probability resolution of the simulation is limited to increments of 1/1000 or 0.01%. The values reported in the following tables are rounded to the nearest 1% value to simplify discussion. Values shown to be less than 1% in the tables represent probabilities of failure of less than 0.50%. In other words, <1% represents the occurrence of less than 50 failures in the 1000 panels that were analyzed in the simulation. The shaded regions represent failure probabilities greater than 10%.

Table 21. Probabilities of Failure for Batch 1

Skin Thickness (in.)	Core Thickness (in.)						
	1.5	1.75	2	2.25	2.5	2.75	3
0.15	100%	100%	98%	83%	56%	33%	17%
0.2	96%	75%	43%	22%	9%	4%	1%
0.25	54%	25%	10%	3%	1%	<1%	<1%
0.3	19%	5%	1%	<1%	<1%	<1%	<1%
0.35	5%	1%	<1%	<1%	<1%	<1%	<1%

Table 22. Probabilities of Failure for Batch 2

Skin Thickness	Core Thickness						
	1.5	1.75	2	2.25	2.5	2.75	3
0.15	100%	92%	57%	27%	12%	5%	2%
0.2	55%	22%	8%	2%	1%	<1%	<1%
0.25	12%	3%	1%	<1%	<1%	<1%	<1%
0.3	2%	<1%	<1%	<1%	<1%	<1%	<1%
0.35	<1%	<1%	<1%	<1%	<1%	<1%	<1%

Table 23. Probabilities of Failure for Batch 3

Skin Thickness (in.)	Core Thickness (in.)						
	1.5	1.75	2	2.25	2.5	2.75	3
0.15	100%	100%	94%	77%	53%	35%	21%
0.2	93%	67%	41%	22%	11%	6%	3%
0.25	50%	24%	11%	5%	3%	1%	1%
0.3	17%	7%	3%	1%	1%	<1%	<1%
0.35	6%	2%	1%	<1%	<1%	<1%	<1%

Table 24. Probabilities of Failure for Batch 4

Skin Thickness (in.)	Core Thickness (in.)						
	1.5	1.75	2	2.25	2.5	2.75	3
0.15	98%	83%	63%	47%	34%	23%	16%
0.2	61%	42%	27%	17%	11%	7%	5%
0.25	32%	18%	11%	7%	4%	3%	2%
0.3	14%	8%	5%	3%	2%	1%	1%
0.35	8%	4%	2%	2%	1%	1%	1%

Table 25. Probabilities of Failure for Batch 5

Skin Thickness (in.)	Core Thickness (in.)						
	1.5	1.75	2	2.25	2.5	2.75	3
0.15	100%	100%	93%	76%	53%	32%	19%
0.2	92%	67%	42%	22%	11%	5%	2%
0.25	51%	25%	11%	4%	2%	<1%	<1%
0.3	19%	8%	2%	1%	<1%	<1%	<1%
0.35	6%	2%	<1%	<1%	<1%	<1%	<1%

Table 26. Probabilities of Failure for All Batches Combined

Skin Thickness (in.)	Core Thickness (in.)						
	1.5	1.75	2	2.25	2.5	2.75	3
0.15	100%	95%	79%	54%	34%	20%	13%
0.2	76%	47%	25%	13%	6%	4%	2%
0.25	30%	14%	6%	3%	2%	1%	<1%
0.3	11%	5%	2%	1%	<1%	<1%	<1%
0.35	4%	1%	1%	<1%	<1%	<1%	<1%

The range of primary parameters (skin and core thickness) in Table 21 through Table 26 bound the design problem in terms of possible failure probabilities (<1%-100%). It was assumed that a single lamina was 0.010-in thick and the core was available in 0.25-in thick increments. Panel failure probability was determined almost exclusively by failure of the lamina making up the sandwich skins. According to the analyses, the likelihood of core shear failure was relatively insignificant.

6.1.9 Discussion

The tables of panel probabilities provide designers and decision makers with information to assess the performance associated with each design case. Decision makers can then trade-off performance with other considerations such as weight and cost impacts. The cells in the upper left-hand region of the tables represent the panel designs which use the least amount of material resulting in the lowest weight and cost. This region is considered the most favorable or "best" solution area. Conversely, the table's lower right-hand region results in using the most amount of material and can be considered the least favorable or "worst" solution area, as well as the "safest" area.

Implications of the panel failure probabilities can be explored by expanding a typical decision scenario. We begin with the assumption that a 10% chance of failure due to a blast load is an acceptable amount of structural capability. This assumption recognizes that a 0% chance of failure is unrealistic and efforts to obtain it will have a severe cost and weight impact, and also recognizes that the failure definition implies local failure of the panel, and not overall rupture. It also assumes that the likelihood of blast occurrence is conservative and small and therefore the risk associated with using a 10% chance of failure is acceptable. Gray shaded regions in Table 21 through Table 26 indicate unacceptable designs, i.e., designs that result in more than a 10% probability of failure based on the current reliability model and associated information and assumptions. Comparing the material properties for Batches 1 through 5, listed in Table 14 through Table 19, with their corresponding failure probabilities shows that similar levels of acceptable designs result from each of the manufacturers, with Batch 2 providing a more ideal range of acceptable designs. If the threshold of acceptability is changed to be a 1% allowable probability of failure, Batch 2 remains dominant with 21 acceptable designs, while Batch 4

becomes the least desirable with only 5. Comparing Batch 2 to the combined failure probabilities in Table 26 shows the benefits of using fabricator-specific, material design properties versus pooling all data as one population. Use of the combined data is not recommended, as the Batch sample data cannot be shown to be from the same population with any reasonable confidence. Allowing for use of fabricator specific material property characterizations provides a means of addressing variations in the fabrication process such that better processes are rewarded directly and not handicapped by an averaging across the population of fabricators.

One can make observations on the effect of using ANOVA generated, B-basis allowables for panel design. The same range of panel designs is analyzed using the same predictive tool. All the variables are fixed at their mean values except the material properties (elastic constants and strengths), in which case the B-basis values are used as listed in Table 27.

Table 27. B-basis: Probability of Panel Failure

Skin Thickness (in)	Core Thickness (in)						
	1.5	1.75	2	2.25	2.5	2.75	3
0.15	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
0.20	FAIL	FAIL	FAIL	FAIL	FAIL	PASS	PASS
0.25	FAIL	FAIL	FAIL	PASS	PASS	PASS	PASS
0.30	FAIL	PASS	PASS	PASS	PASS	PASS	PASS
0.35	PASS	PASS	PASS	PASS	PASS	PASS	PASS

Using the ANOVA B-basis allowables gives approximately the same results as the majority of the results based on individual batch material properties, but penalizes the fabricator of Batch 2. A factor of safety of 1.0 is used in this analysis. If a factor of safety greater than one is applied, the number of successful panel designs would be reduced, further penalizing the design. Even with a 1% probability of failure acceptability threshold, Batch 2 has 21 acceptable designs, which is significantly more than supported by the other batches. The resulting increase in skin and core thickness could significantly impact the design if the structural system is either cost or weight critical. Under the proposed methodology, experimental testing of material samples defines a set of probabilistically characterized material allowables (Table 14 through Table 18) for design. Hence, unique sets of material allowables are determined for each fabricator and a more accurate measure of the capability performance is provided. The reliability-based, decision process allows the benefits of using composites, reduced weight and least cost, to be more fully realized.

6.1.10 Conclusions

The use of reliability-based methods to determine the capability performance of the composite structure against dynamic, lateral pressure loading is presented. Comparison is made of reliability approach to the use of traditional pass/fail criteria supported by material allowables developed using MIL-HDBK-17. Table 28 shows that the use of a 99 or 90 percent reliability top-level requirement for the structural capability performance, Co', favors the use of a structure built by the fabricator of Batch 2. The use of B-Basis allowables for design provides the same number of successful design as would the use of the fabricators of Batches 1, 3, 4 and 5 at a 90 percent reliability, while it would reduce the number of possible designs associated with Batch 2 at either the 90 or 99 percent levels. This case study demonstrates that a reliability-based, capability measurement allows much greater latitude and control on the part of the designer to ensure optimal performance. The inclusion of fabricator specific material property information allows the ship design manager to take advantage of improvements in manufacturing techniques by a subset of the manufacturing community that would support greater levels of performance relative to fabrication costs. This control also supports mitigation of associated risks with a more formal and traceable design process.

Table 28. Number of Successful Designs For Different Top-Level Requirements on Capability Performance

Batch	Co' > 99% (P_f < 1%)	Co' > 90% (P_f <10%)
1	15	21
2	21	27
3	11	19
4	5	19
5	11	19
Combined	12	21
B-Basis	19	

6.2 UNSTIFFENED PLATE CAPABILITY

Design of an unstiffened plate to withstand lateral loading requires an accurate structural response model. The dominating limit for unstiffened plating tends to be allowable permanent set. Consideration of elastic flexure of the plate is not included in design formulations concerned with strength, but this may prove important if ship system effects such as vibration are considered. The radar cross section of a ship can be influenced by the geometry chosen for the ship structure. In an effort to make Navy ships less visible, the structure can be configured using flat surfaces such that the radar cross section is optimized (NAWC 1999). This consideration would require maintaining some degree of side-shell plating flatness in the face of wave loadings. The structure's capability to support this flatness requirement must be ensured using a quantitative performance measure.

This case study demonstrates currently available methodologies for designing unstiffened plating against excessive permanent set, and the traditional limitations used to judge when failure

has occurred. A procedure is demonstrated for addressing vague failure definitions using subjective probabilities, as discussed in Chapter 4, to capture historically accepted permanent set limitations.

6.2.1 Permanent Set Prediction Models

Consider a plate of 96 inches in length and 24 inches in breadth, for an aspect ratio (α) of 4. This plate may be part of a stiffened panel subject to hydrostatic pressure in the lower shell of a ship. The panel is to be made from ordinary steel (F_Y = 34000psi). The US Navy *Structural Design Manual for Naval Surface Ships* (US Navy 1976) provides an easy algorithm for determining the appropriate plate thickness based on C values according to the following equation:

$$\frac{b}{t} \leq \frac{C}{K\sqrt{H}} \tag{6-5}$$

where b is the short dimension of the plate (stiffener spacing) in inches; t is the plate thickness in inches. H is the design head of sea water in feet, which for demonstration purposes we will take as 30 feet (for a pressure of 13.33 pounds per square inch or psi). K is a shape factor determined by the inverse of the aspect ratio, b/a or $1/\alpha$, which for $b/a \leq 0.5$ is unity. The C factor for ordinary steel is found in Table 29 to be 550. This gives a required plate thickness of 0.239 inches, requiring the use of the next available plate thickness, which is ¼ inch. The US Navy design pressure corresponding to this thickness is 14.59 psi. The plate slenderness ratio, B, is 3.2536 where B is defined by:

$$B = \frac{b}{t}\sqrt{\frac{F_Y}{E}} \tag{6-6}$$

Table 29. C Values for Steel Types and Locations of a Ship (U.S. Navy 1976)

Material Type	Ultimate Tensile Strength (ksi)	Yield Strength (ksi)	Top Side	Lower Shell/Tank	Flooding/ Damage Control
MS (OS)	60	34	350	550	700
HTS	72	47	400	630	800
HY-80 (HSLA80)	100	80	500	750	900
HY-100	115	100	550	800	1000

The C factors are derived from a rearrangement of simple beam theory using Equation 6-7, with the stress due to the lateral pressure given by f_a and γ is the density of seawater. For topside regions, the stress is limited to the allowable working stress of the material, with the intent of preventing any permanent set. For ordinary steel, this is 27 ksi resulting in C = 350. For lower

shell regions, the C values are calculated by allowing f_a to go to twice the yield strength, resulting in a moderate degree of permanent set. The tank regions allow the formation of membrane stresses, with a f_a approximately twice the ultimate tensile strength according to Equation 6-7.

$$f_a = \frac{12\,\gamma H b^2 t}{12{*}144{*}2\,t^3} \tag{6-7}$$

The plastic structural response of an unstiffened plate subjected to a uniform lateral load may be modeled with a variety of approximations, three of which will be discussed below. The example plate will be used to show the response as a function of load for each of the three formulations, along with traditional limiting values for the permanent set.

The American Petroleum Institute's 1987 *Bulletin* 2V (API 1987) gives the formulation for finding the lateral pressure associated with a specified permanent set (w_p) shown by Equation 6-8. Rearrangement provides Equation 6-9, which shows the permanent set as a function of lateral pressure. These equations provide a linear relationship between pressure and permanent set.

$$P = F_Y\left(\frac{t}{b}\right)^2 \frac{6}{\sqrt{\alpha}}\left[1 + \frac{2}{\alpha}\frac{w_p}{t}\right] \tag{6-8}$$

$$w_p = \frac{\alpha t}{2}\left[\frac{P}{F_Y}\left(\frac{b}{t}\right)^2 \frac{\sqrt{\alpha}}{6} - 1\right] \tag{6-9}$$

A second, more complex formulation for finding the lateral pressure associated with a permanent set is presented in Hughes (1988, Equation 9.4.1), and is shown in Equation 6-10.

$$Q = Q_Y + T(R_w)[\Delta Q_0 + \Delta Q_1 R_w] \tag{6-10}$$

$$Q = \frac{PE}{F_Y^2}$$

$$Q_Y = \frac{2}{\sqrt{1-\nu+\nu^2}\;B^2}\left[1 + 0.6\left(\frac{b}{a}\right)^4\right]$$

$$\Delta Q_0 = \frac{1 + 0.5B\frac{b}{a}\left[1 + \frac{b}{a}\left(3.3 - \frac{1}{B}\right)\right]}{\sqrt{1-\nu+\nu^2}\;B^2}$$

$$\Delta Q_1 = 0.32\left(\frac{b/a}{\sqrt{B}}\right)^{1.5}$$

$$\begin{aligned} T(R_w) &= \left[1-(1-R_w)^3\right]^{1/3} && R_w \le 1 \\ &= 1 && R_w > 1 \end{aligned}$$

$$R_w = w_p \left[\frac{0.07B^2}{3} \right]^{-1}$$

A third formulation is provided from a study done by Bruchman and Dinsenbacher (1991) using non-linear finite element models to arrive at the empirical relation shown in Equation 6-11.

$$w_p = b\left(\frac{PEB^2}{2.222F_Y^2} - 1\right)^3 \left[0.00356 + 0.0198 \tanh\left(\frac{B}{60}\sqrt{\frac{E}{F_Y}}\right)\right] \tag{6-11}$$

The API (1987) limiting value for permanent set is shown by Equation 6-12, resulting in an allowed permanent set of 0.163 inches for the example plate.

$$w_{p,\max} = 0.2tB \tag{6-12}$$

Hughes (1988) provides two limiting values of permanent set:

$$w_{p,\max} = 0.01b \text{ for Cargo Vessels, and} \tag{6-13}$$

$$w_{p,\max} = 0.02b \text{ for Naval Vessels.} \tag{6-14}$$

For the example plate, the limiting values for the commercial and naval applications are 0.24 and 0.48 respectively.

The plot of the three formulations as permanent set as a function of applied lateral pressure is shown in Figure 11. It can be seen that the three formulations provide different values of permanent set for a given lateral pressure. It is interesting to note that the limiting value of permanent set from Equation 6-12 (API 1987) is almost equivalent to the response due to the US Navy's design pressure as predicted by Equation 6-8 (API 1987). Similarly, the limiting permanent set found using Equation 6-13 (Hughes 1988) corresponds closely to the response predicted using Equation 6-11 (Bruchman and Dinsenbacher 1991) under the US Navy design pressure.

The variation of the lateral pressures associated with each failure definition is rather large as shown in Table 30. This variation is due to vagueness of the failure definition. The Navy requirement shown as a limiting lateral pressure for the panel allows for the permanent set predicted by the three algorithms to range from 0.07 to 0.25 as shown in Table 31. The limiting response, or failure threshold, is therefore highly dependent on the model chosen for its prediction.

Table 30. Pressures Predicted by Three Response Models for Three Failure Definitions of Example Unstiffened Panel under Lateral Loading

Failure Definition (allowable permanent set)	Lateral Pressure from Equation 6-8 (API 1987)	Lateral Pressure from Equation 6-10 (Hughes 1988)	Lateral Pressure from Equation 6-11 (Bruchman and Dinsenbacher 1991)
Equation 6-12 (API 1987)	14.67 psi	15.74 psi	13.73 psi
Equation 6-13 (Cargo Vessels, Hughes 1988)	16.38 psi	16.05 psi	14.51 psi
Equation 6-14 (Naval Vessels, Hughes 1988)	21.69 psi	16.68 psi	16.15 psi

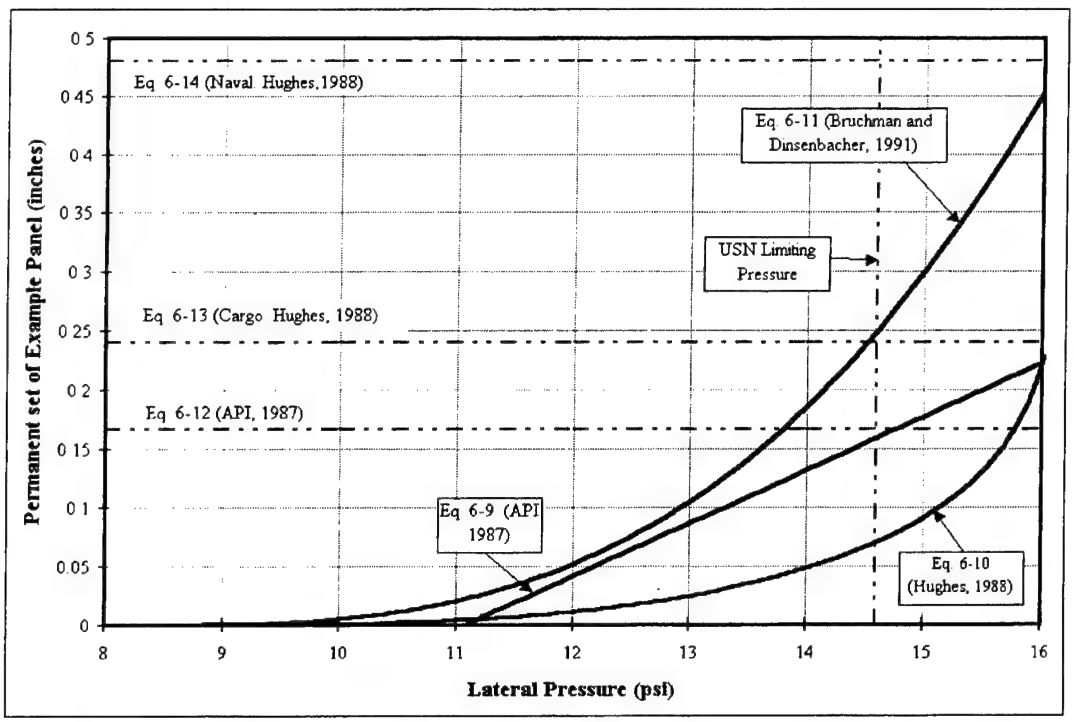

Figure 11. Permanent Set Predictions versus Lateral Pressure for Example Unstiffened Panel

Table 31. Permanent Set Associated with the Design Pressure of 14.59 psi, Predicted by Three Response Models

Response Model	Equation 6-9 (API 1987)	Equation 6-10 (Hughes 1988)	Equation 6-11 (Bruchman and Dinsenbacher 1991)
Permanent Set	0.159 in.	0.071 in.	0.249 in.

6.2.2 Reliability Analysis of Unstiffened Plate

The methodology for probabilistic characterization of the failure definition, or threshold, mentioned in Chapter 4 will be applied to the reliability analysis of the unstiffened plate under lateral pressure example.

Development of a new, probabilistic limit state, which combines the limit states presented in Equations 6-12, 6-13, and 6-14, may take place with the use of Bayesian probability methods. To simplify the example, one may assume the limit states are normally distributed allowing the combination of the three limit states into one, normally distributed random variable.

Equation 6-15 shows Bayes' Theorem, which is the means for aggregating the limit state distributions.

$$\Pr(\vartheta \mid \varepsilon) = \frac{\Pr(\varepsilon \mid \vartheta)\Pr(\vartheta)}{\Pr(\varepsilon)} \tag{6-15}$$

$\Pr(\vartheta)$ is the *prior distribution* of random variable ϑ; $\Pr(\vartheta|\varepsilon)$ is the *posterior distribution* of ϑ after being updated with the evidence ε; and $\Pr(E|\vartheta)/\Pr(\varepsilon)$ is the *relative likelihood* of the evidence given previous knowledge of ϑ is correct (Modarres 1993). If the prior and the likelihood are normally distributed random variables, the posterior is normal as well. This relationship between the prior and likelihood is called a conjugate pair, and allows easy calculation of the posterior distribution parameters. Other conjugate pairs exist for non-normal distributions. The means to accomplish aggregation of two normally distributed random variables is through the use of Equations 6-16 and 6-17.

$$\mu_P = \frac{\sigma_0^2}{\sigma_0^2 + \sigma_1^2}\mu_0 + \frac{\sigma_1^2}{\sigma_0^2 + \sigma_1^2}\mu_1 \tag{6-16}$$

$$\sigma_P = \frac{1}{\sqrt{\frac{1}{\sigma_0^2} + \frac{1}{\sigma_1^2}}} \tag{6-17}$$

The mean and standard deviation of the random variables being combined are μ_0 and σ_0 for the first (prior) and μ_1 and σ_1 for the second (likelihood). The posterior, or the distribution of the combined random variables, is normal with a mean of μ_P and standard deviation of σ_P. The

three distributions may be combined in any order, as Bayes' Theorem is not affected by sequencing effects (additive property).

Averaging is also included as a means of combining the failure thresholds in the analysis. The average of the means is used to gain the combined mean. The sum of the variances is used as the variance of the combined failure thresholds. The standard deviation is the square root of the variance. The results of the combining process are shown in Table 32. The chosen uncertainty levels shown in the table are for demonstration purposes.

Table 32. Permanent Set Failure Threshold

Failure Threshold Formulation	Mean (in)	Standard Deviation (in)	Coefficient of Variation
Equation 6-12 (API 1987)	0.163	0.0163	10%
Equation 6-13 (Cargo Vessels, Hughes 1988)	0.24	0.024	10%
Equation 6-14 (Naval Vessels, Hughes 1988)	0.48	0.024	5%
Combined using Bayes'	0.2655	0.01174	4.42%
Combined using Average	0.2942	0.03764	12.79%

Note: failure thresholds are based on nominal values of the plate scantlings as discussed previously.

As shown in Table 32, the use of Bayes' Theory in combining the failure thresholds leads to a reduction in the uncertainty that is not justified. The increase in the uncertainty using the averaging of the failure thresholds is more appropriate to the level of knowledge associated with the failure thresholds from literature. The level of damage allowed to occur prior to judging the response as failure, is increased if the combined average is used to define the mean allowable permanent set.

The two response models shown in Equations 6-9 and 6-11 are used to calculate the probability of exceeding each limit state for the example plate under lateral loading discussed earlier in this Section. Equation 6-10 was not used due to the complexity involved in predicting the permanent set as a function of pressure. A Monte Carlo simulation with Latin-Hypercube sampling was conducted with 1000 cycles for each response mode and limit state pairing.

The lateral pressure, P, distribution for local seaway on a ship's hull may be modeled using an exponential distribution with the design pressure as its mean (Sikora 1998a). The mean in this case is the US Navy design pressure of 14.59 psi, which gives an exponential distribution parameter, λ, value of 0.06854 psi^{-1}.

The biases and uncertainties associated with the strength variables in the permanent set formulation have been characterized probabilistically as discussed in Hess et al. (1997). These biases are reported as a ratio between the nominal value and the mean of the material samples, and an uncertainty surrounding the bias characterized by a probability density function (PDF.). The simplest probability density function provided in the paper for each basic variable is chosen for this exercise. The yield strength, F_Y, is reported as lognormally distributed with a reported ratio bias of 1.1746 and a standard deviation of 0.1214. For mild steel, the mean yield strength is 39940 psi and has a standard deviation of 4128 psi. The Young's Modulus, E, is reported as being normally distributed and having a mean bias of 0.9868 and a standard deviation of 0.07520. For the mild steel used in this example, the Young's Modulus has a mean of 29.2×10^6 psi and a standard deviation of 2.22×10^6 psi. The panel width, b, is reported as normally distributed with a mean bias of 0.9921 and a standard deviation of 0.02816. The panel width in this example has a resulting mean of 23.81 inches and a standard deviation of 0.6758 inches. The plate thickness, t, is reported as lognormally distributed with a mean bias of 1.048 inches and a standard deviation of 0.045 inches. The plate thickness used in this example has a resulting mean of 0.262 inches and standard deviation of 0.01125 inches.

The reliability analysis of the response predictions versus the five failure thresholds provides exceedance probabilities ranging from 15.9 to 30.4 percent, as shown in Table 33. The average of the exceedance probabilities for Equation 6-9 is 22.4 percent, while for Equation 6-11 the average is 27.3 percent. These are very close to the probabilities shown for both combined limit state cases, and are likely the result of assuming the limit states are normally distributed. The choice of non-normal distributions will likely cause the probability of exceeding the combined limit states to differ from being just the average of the probabilities of exceedance calculated for the independent limit states.

The higher amount of permanent set for a given pressure load given by Equation 6-11 results in higher exceedance probabilities for all limit states as compared to the probability predictions using Equation 6-9. The correlation between the failure threshold selection and the choice of response model has a significant influence on the results of a reliability analysis.

The analytical representation of the response model is very important as well. The example response model in Equation 6-9 predicts a linear relation between the load and the permanent set. This is not indicative of the plastic, non-linear behavior associated with the material. The use of stochastic finite element methods for a numerical response model would be appropriate for detailed studies and calibration, but not useable for design purposes.

Table 33. Probabilities of Exceeding the Maximum Permanent Set According to Different Failure Thresholds and Response Models

Failure Thresholds	Response Models	
	Equation 6-9 (API 1987)	Equation 6-11 (Bruchman and Dinsenbacher 1991)
Equation 6-12 (API 1987)	28.2 %	30.4 %
Equation 6-13 (Cargo Vessels, Hughes 1988)	23.8 %	27.9 %
Equation 6-14 (Naval Vessels, Hughes 1988)	15.1 %	23.7 %
Combined using Bayes'	22.5 %	27.3 %
Combined using Average	21.3 %	26.6 %

More accurate probabilistic limit state definitions can be formulated through aggregation of historical failure data, traditional limit states and expert opinion. A probabilistic characterization of historic deformation failures may be blended with the traditional design goals (limiting permanent set) in order to improve future designs. The use of expert opinion is implicit in using historical data, as the degree of deformation considered as failure, tends to be subjective in practice.

6.2.3 Conclusions

This case study demonstrates currently available methodologies for designing unstiffened plating against excessive permanent set, and the traditional limitations used to judge when failure has occurred. A procedure is demonstrated for addressing vague failure definitions using subjective probabilities, as discussed in Chapter 4, to capture historically accepted permanent set limitations.

An example is presented of structural serviceability failure of an unstiffened plate experiencing permanent deformation due to lateral pressure. Excessive permanent set may misalign a mechanical system rendering it inoperable, reduce the strength of a larger structural system beyond acceptable levels and endanger more critical systems, or be cosmetically unappealing. The consequence of the permanent deformation may also be an increase in the likelihood of greater system failures or an increase in the radar cross section of a ship. The point at which the deformation level becomes unacceptable for the designer or surveyor is the onset of failure for the plate. The failure definition for the permanent set of unstiffened plating depends on the acceptability of the consequences of the permanent set. When the consequences are no longer acceptable, the plate has failed. Different response prediction models and failure

thresholds are presented and compared to show their importance in a reliability-based design process. The importance of "flat" surfaces in Naval applications may be a future source of rational, quantitative allowable permanent set prescriptions which would benefit from probabilistic characterization.

The traditional failure definitions lead to a significant probability of failure for the example presented above and as shown in Table 33. The recommended result defining the capability of a Navy panel is 23.7 percent probability of failure. This was predicted using the Navy limit presented by Hughes (1988) and the advanced response model developed at NSWCCD (Bruchman and Dinsenbacher 1991). The sensitivity of the probability of failure is shown to be highly dependent upon the chosen response model and failure threshold. To effectively support a capability measure, the methods presented in this case study will require greater emphasis to be placed on the predictive models and supporting information in order to validate the usability of the results for decision-making.

6.3 HULL GIRDER DEPENDABILITY

This case study addresses the dependability performance of the primary hull structure for the notional destroyer. The probability of collapse failure of the hull girder due to seaway bending is considered. The associated limit state equations, load and load uncertainty information, strength and strength uncertainty information and a subsequent reliability analysis will be presented and discussed.

6.3.1 Hull Girder Collapse Failure

Two hull girder limit state equations can be formulated to address hull girder collapse under vertical bending. Failure is defined as the point at which the applied wave bending moment exceeds the maximum resisting bending moment. The limit state equations are as follows:

$$B_u M_u \geq B_{SW} M_{SW} + \mathrm{k}_{\mathrm{W}} \left(B_W M_W + k_D \, B_D M_D \right) \tag{6-18}$$

$$B_u M_u \geq B_{SW} M_{SW} + k_{WD} \, B_{WD} M_{WD} \tag{6-19}$$

where:

B_D = modeling bias and uncertainty (real/predicted) of M_D

B_{SW} = modeling bias and uncertainty (real/predicted) of M_{SW}

B_u = modeling bias and uncertainty (real/predicted) of M_U

B_W = modeling bias and uncertainty (real/predicted) of M_W

B_{WD} = modeling bias and uncertainty (real/predicted) of M_{WD}

k_D = dynamic bending moment probabilistic combination load factor

k_W = wave-induced bending moment probabilistic combination load factor

k_{WD} = probabilistic combination load factor for combined wave-induced and whipping

M_D = dynamic bending moment

M_{SW} = stillwater bending moment

M_u = ultimate bending capacity of ship hull girder

M_W = wave-induced bending moment

M_{WD} = combined wave-induced and whipping bending moment

Rearrangement of the limit state equations results in the performance functions shown in Equations 6-20 and 6-21. The input load and strength components for these performance functions are no longer the nominal values, but are to be considered as random variables with associated uncertainty characterizations. When g_{HG} is less than zero, failure is assumed to have occurred. The input components to the performance functions will be developed below.

$$g_{HG1} = B_u M_u - B_{SW} M_{SW} - k_W \left(B_W M_W + k_D B_D M_D \right) \tag{6-20}$$

$$g_{HG2} = B_u M_u - B_{SW} M_{SW} - k_{WD} B_{WD} M_{WD} \tag{6-21}$$

The wave (M_W) and dynamic (M_D) bending moments are predicted by the US Navy code SPECTRA Version 8.2 (Michaelson 2000) and combined automatically into the combined bending moment, M_{WD}, supporting the use of Equation 6-21. The predicted output is in the form of a shifted, or 3-parameter Weibull distribution. The stillwater and wave components are assumed to be independent, thus k_{WD} is set equal to 1.0. For the purposes of this reliability analysis demonstration, Equation 6-21 becomes:

$$g_{HG2} = B_u M_u - B_{SW} M_{SW} - B_{WD} \left(Trunc + M_{WD} \right) \tag{6-22}$$

where M_u is the ultimate bending capacity of ship hull girder as generated by the US Navy code ULTSTR (Adamchak 1982). For simple analyses, this value can be produced using nominal basic strength values. For complex analyses, the prediction is conducted using probabilistic characterizations of all the basic variables upon which the strength prediction is based. The uncertainty (a.k.a., bias) of ultimate bending capacity of ship hull girder prediction by ULTSTR is B_u. For simple analyses, this variable represents the total bias of the ULTSTR prediction (Real/Nominal-Prediction) using nominal inputs for basic strength variables, and is a random variable with a probabilistic characterization. For more complex analyses, this variable represents the modeling uncertainty (Real/Adv.-Prediction), and is a random variable with a probabilistic characterization.

The load information consists of stillwater and wave bending moments and biases. The nominal value of stillwater bending moment, M_{SW}, is produced by the computer code SHCP (Rosborough 2001). B_{SW} is the total bias (Real/Nominal) for the stillwater bending moment, nominal prediction by SHCP. This value is assumed to be normally distributed with a mean of 1.0 and a standard deviation of 0.02. Combined wave-induced plus whipping, hull girder bending moment prediction is M_{WD}. The randomness of the maximum lifetime load is included in the SPECTRA prediction as a random variable with a Weibull distribution. SPECTRA reports the Weibull distribution parameters (scale and slope) along with a truncation value (location parameter). *Trunc* is the "Truncation" value from SPECTRA, which serves as a location parameter for the Weibull distribution characterizing the wave plus whipping, hull girder bending moment. This value is non-varying. B_{WD} is the total bias for maximum lifetime load prediction from SPECTRA. This value is produced using a first order approximation to combining the wave and dynamic uncertainties. The development of these limit state parameters is discussed below.

6.3.2 Hull Girder Bending Strength

The hull girder of a surface ship is designed to resist the wave-induced bending resulting from wave actions in a seaway. The hull-girder wave bending moments are considered the primary loadings on the ship structure and result in longitudinal stresses throughout a cross-section. Ships are traditionally idealized as a beam and divided into 20 stations, with Station 0 at the forward perpendicular (FP), Station 10 at the midship section, and Station 20 at the aft perpendicular (AP). The stations provide reference points for consideration of the non-prismatic nature of the ship hull-form, and provide a discretization of the structure. This discretization simplifies the task for the designer to a matter of ensuring the primary loads at each section are resisted.

The hull girder is defined as the ship structure between the strength deck and the keel. The deckhouse is not considered part of the hull girder in keeping with the current US Navy practice. The inclusion of the deckhouse would also violate the linear strain distribution assumption currently used in ULTSTR. The discontinuous nature of the deckhouse and use of materials other than steel cause the deckhouse to react differently than the hull structure, and cause nonlinearity in the curvature-induced strain distribution through the cross section. The main or strength deck is the uppermost, full-length deck designed to resist primary bending of the ship. Traditional consideration of effective material will be used in determining the structure to be included in the analysis. For example, the shadow regions fore and aft of an opening as shown in Figure 12, are not included as effective material in determining the cross sectional properties, such as moment of inertia and area, nor in determining the strength of the hull girder at a section. The effectiveness of non-continuous decks and platforms will be considered in accordance with current Navy practice.

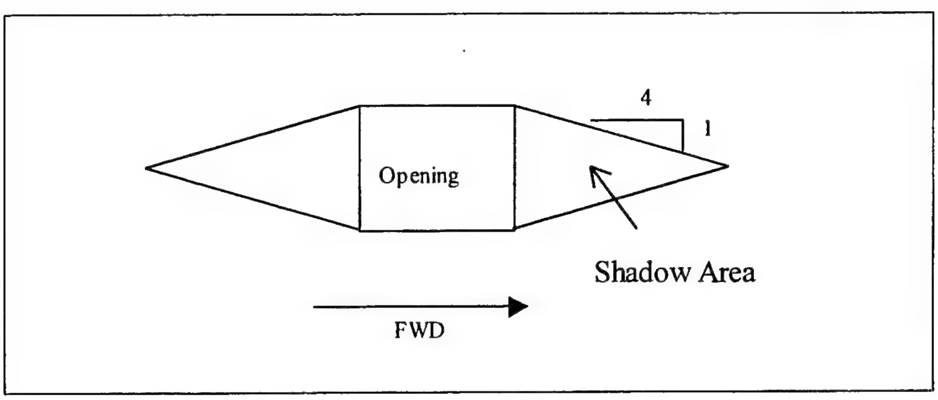

Figure 12. Ineffective Structural Shadow Regions Around Openings

Two forms of strength prediction models are considered. The first is the elastic-based strength approach. The second is the incremental-strain approach, which is iterative in nature. The uncertainty associated with each strength prediction model will be explored in Sections 6.3.2.3 and 6.3.2.4.

6.3.2.1 Elastic-Based Hull Girder Ultimate Strength

The elastic-based strength depends upon on an approximate relation between the hypothetical onset of yield failure in the extreme fiber, and the buckling of critical panels such that the ultimate strength of the hull has been reached. The vertical moment of inertia of the cross-section about the elastic neutral axis, I_{NA}, is to be calculated and coupled with the distance to the deck and keel extreme fiber, y_{deck} and y_{keel} to form the section modulus, Z, as follows:

$$Z_K = \frac{I_{NA}}{y_{keel}} \tag{6-23}$$

The stress at the extreme fiber is given by elastic structural theory as:

$$f = \frac{M}{Z} \tag{6-24}$$

which may be rearranged as:

$$M = f\,Z \tag{6-25}$$

The bending capacity of the hull coinciding with yielding in the extreme fiber is therefore:

$$M_Y = F_Y Z \tag{6-26}$$

It has been proposed that a reasonably consistent fraction of M_Y corresponds to the moment at which hull girder collapse occurs, M_u, due to buckling (Mansour et al. 1996; Atua 1998). This fraction, known as the buckling knockdown factor c, is the ratio of M_u to M_Y. The resulting estimate of M_u is:

$$M_u = cF_Y Z \tag{6-27}$$

An analysis has been done of the knockdown factor, c, for multiple Navy ships to ascertain the appropriateness of values found in the literature. The ultimate bending strength of the midship section is determined by ULTSTR. This bending strength prediction is divided by the elastic bending strength, M_Y, to calculate c as shown in Equation 6-28.

$$\mathrm{c} = \frac{M_u}{F_y Z} \tag{6-28}$$

SSC-392 (Mansour et al. 1996) recommends values of 0.8 for MS and 0.6 for HS. Atua (1998) developed values of 0.36 for hog and 0.74 for sag as a result of an analysis of c along the length of a Navy cruiser. In this report, the variation in c amidships for a range of combatant classes was investigated. The following figures and tables show the variation of the knockdown factor in hog and sag loading for a frigate, two destroyers, a cruiser and an amphibious assault ship. Figure 13, Table 34 and Table 35 use the yield strength of the plate to determine the knockdown factor, while Figure 12, Table 36 and Table 37 use the yield strength of the stiffener.

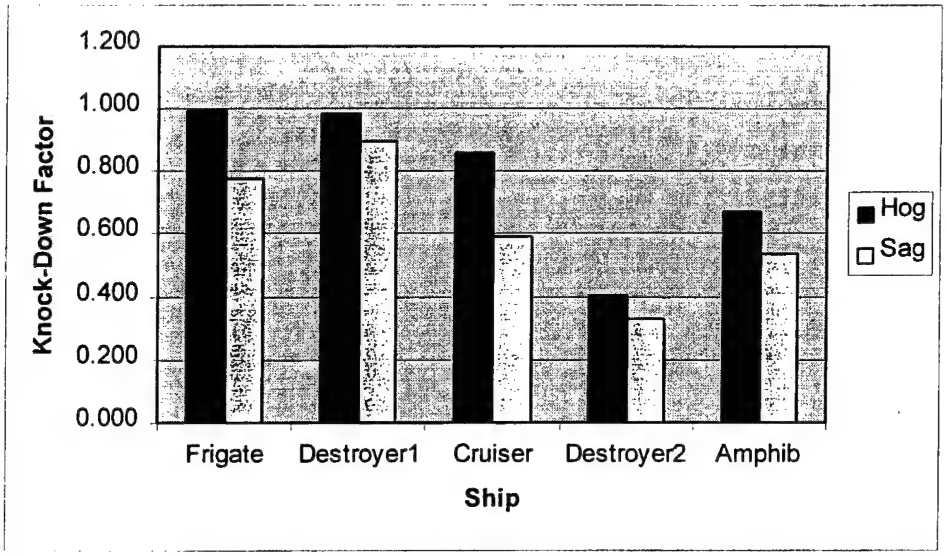

Figure 13. Hull Girder Ultimate Strength Knockdown Factors Based on Plate Yield Strength

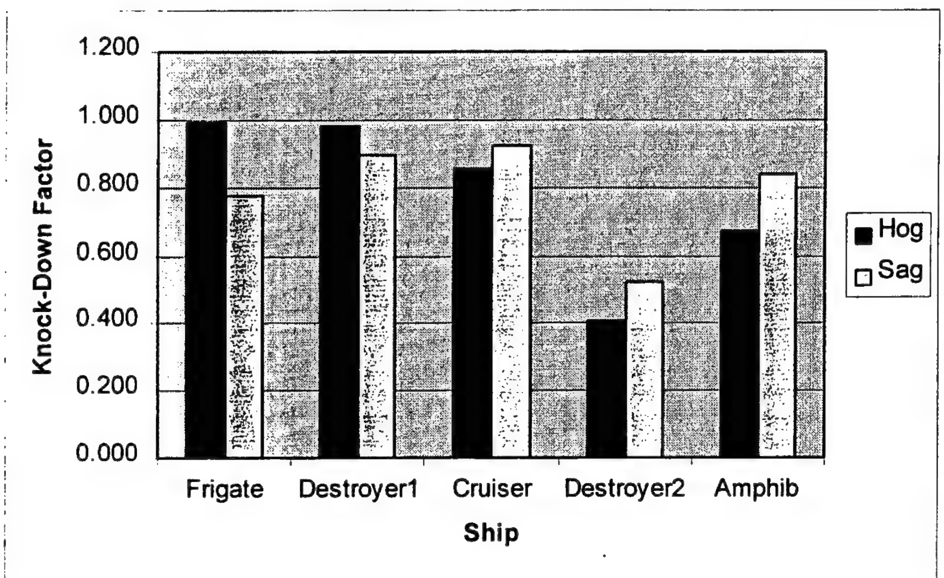

Figure 14. Hull Girder Ultimate Strength Knockdown Factors Based on Stiffener Yield Strength

Table 34. Hull Girder Hogging Ultimate Strength Knockdown Factors for Five Navy Ships, Based on Plate Yield Strength

Ship	M_u from ULTSTR (ft-ltons)	Z to Keel (in^2-ft)	Yield Strength, F_Y (ksi)	Knockdown Factor, c
Frigate	149200	9897	34	0.993
Destroyer 1	395410	26581	34	0.980
Cruiser	815908	26624.3	80	0.858
Destroyer 2	349200	24020	80	0.407
Amphib	4287701	178028	80	0.674
			Mean =	0.783
			COV =	31%

Table 35. Hull Girder Sagging Ultimate Strength Knockdown Factors for Five Navy Ships, Based on Plate Yield Strength

Ship	M_u from ULTSTR (ft-ltons)	Z to Keel (in^2-ft)	Yield Strength, F_Y (ksi)	Knockdown Factor, c
Frigate	126900	10756	34	0.777
Destroyer 1	333000	24419	34	0.898
Cruiser	493263	23445.3	80	0.589
Destroyer 2	306793	25920	80	0.331
Amphib.	3293490	172375	80	0.535
			Mean =	0.626
			COV =	35%

Table 36. Hull Girder Hogging Ultimate Strength Knockdown Factors for Five Navy Ships, Based on Stiffener Yield Strength

Ship	M_u from ULTSTR (ft-ltons)	Z to Keel (in^2-ft)	Yield Strength, F_Y (ksi)	Knockdown Factor, c
Frigate	149200	9897	34	0.993
Destroyer 1	395410	26581	34	0.980
Cruiser	815908	26624.3	80	0.858
Destroyer 2	349200	24020	80	0.407
Amphib.	4287701	178027.9	80	0.674
			Mean =	0.783
			COV =	31%

Table 37. Hull Girder Sagging Ultimate Strength Knockdown Factors for Five Navy Ships, Based on Stiffener Yield Strength

Ship	M_u from ULTSTR (ft-ltons)	Z to Keel (in^2-ft)	Yield Strength, F_Y (ksi)	Knockdown Factor, c
Frigate	126900	10756	34	0.777
Destroyer 1	333000	24419	34	0.898
Cruiser	493263	23445.3	51	0.924
Destroyer 2	306793	25920	51	0.520
Amphib.	3293490	172375	51	0.839
			Mean =	0.792
			COV =	20%

The variation in the knockdown factors from this analysis does not support the use of an elastic-based, ultimate strength prediction for use in decisions on the performance, or reliability,

of the hull girder against collapse. While use of such procedures is attractive due to its relative simplicity, the cost may be excessive as a result of the rather high coefficients of variation (COVs), which range from 20 – 35%. It is also important to note that these numbers are themselves uncertain due to the small sample size. The importance of minimizing this failure likelihood must be supported with equivalent levels of effort in the reliability analysis process through the use of a high-level approach in a computer code such as ULTSTR.

6.3.2.2 Hull Girder Ultimate Strength Based on ULTSTR

The second strength model is the incremental strain method as embodied in ULTSTR (Adamchak 1982). This approach determines the resisting moment as a function of the curvature at each section for increasing levels of curvature. The level of curvature is increased in increments, starting at zero curvature. The strain profile through the cross section is considered linear. The resistance afforded by the individual structural components is calculated for the prescribed level of strain associated with the applied curvature. Each structural component's contribution to the resisting moment is in the form of load-shortening curves which provide an empirical relationship between the level of applied strain and the resulting, resisting stress in the component. The stresses in the entire cross section are calculated such that the section is in equilibrium for the stated curvature; then, the combined resistance stresses are used to compute the overall resisting bending moment. When the resisting moment stops increasing and begins to decrease with increasing curvature, the slope of the moment-curvature curve has become zero and the maximum bending capacity of the hull is reached. ULTSTR data files have been developed for the notional US Navy combatant under consideration in this report.

The use of ULTSTR to develop a serviceability failure definition is possible by assessing the weakest link in the hull girder cross-section. The first ULTSTR element to experience excessive damage can be considered the first failed member. This failure will be the lower bound on the damage spectrum associated with structural failure due to hull girder bending. The system effects may or may not also be damaged before this point. Afterward, the likelihood of system deterioration increases with the increasing damage experienced by the hull structure.

ULTSTR models were constructed for stations 5 through 15 of the notional destroyer. In each case the geometry of the external hull plating was taken from the files used in the Ship Hull Characterization Program (SHCP). Scantlings of internal structure were taken from the appropriate contract drawings.

6.3.2.3 Strength Modeling Uncertainty

The strength prediction model ULTSTR contains approximations and assumptions, which may lead to errors in predicted hull girder collapse strength. The degree of error due to these approximations remains to be adequately quantified across the range of ships. Atua (1998) suggests a normal distribution and a COV of 15% for the ULTSTR prediction of M_u. Based on Monte Carlo simulation calculations for the midship section collapse strengths of four Navy combatants, the upper bound of prediction uncertainty due to basic variable uncertainty was seen to be approximately 10%. This value was used in the spreadsheet reliability analyses to account for randomness in the input variables. No modeling uncertainty is added due to a lack of information.

6.3.2.4 Basic Variable Uncertainty

The uncertainty inherent in the basic strength variables must be included in the performance functions. The information gained from the ship drawings will specify the nominal values for each of the input variables. The mean values of these input variables were decided based upon the uncertainty analyses conducted by Hess, Bruchman and Ayyub (1997) and are summarized in Table 38, Table 39 and Table 40. For the spreadsheet-based reliability analyses, the uncertainty from the basic strength variables as propagated through ULTSTR is accounted for in the COV of 10% as noted in the previous section.

Table 38. Geometric Basic Strength Uncertainty Information

Geometry Component	Distribution	Ratio Bias	COV
Plate Thickness	Lognormal	1.05	0.035
Transverse Web Frame Spacing	Normal	0.992	0.028
Effective Length, Euler Beam-Column Buckling	Lognormal	0.988	0.046
Effective Length, Stiffener Tripping	Lognormal	0.988	0.046
Stiffener Depth	Normal	0.996	0.019
Stiffener Web Thickness	Extreme Value Type I	1.244	0.083
Stiffener Flange Breadth	Lognormal	1.014	0.016
Stiffener Flange Thickness	Extreme Value Type I	1.132	0.092

Table 39. Material Yield Strength Uncertainty Information

Steel Grade	Distribution Type	Nominal (ksi)	Ratio Bias	Mean (ksi)	COV
Mild	Lognormal	34	1.300	44.20	0.124
HTS	Lognormal	51	1.190	60.71	0.083
HY-80	Lognormal	80	1.196	95.66	0.085
HSLA-80	Lognormal	80	1.076	86.01	0.034

Table 40. Elastic (Young's) Modulus Uncertainty Information

Steel Grade	Distribution Type	Nominal (ksi)	Ratio Bias	Mean (ksi)	COV
All	Normal	29.6E+06	0.987	29.2E+06	0.076

6.3.3 Hull Girder Wave Loading

6.3.3.1 Stillwater Bending Loads

The 2nd-order strip theory code SHCP (Rosborough 2001) was used to develop the stillwater bending profile for the notional destroyer. The stillwater bending moments are shown in Table 41 for stations 5 through 15.

Table 41. Design Stillwater Bending Moments

Station	M_{SW} (ft-Ltons)
5	27683.4
6	34128.7
7	40795.6
8	47734.6
9	53527.5
10	56296.9
11	55197.9
12	51488.5
13	45665.6
14	36945.8
15	26664.6

Note: Sign convention is positive for hog.

6.3.3.2 Stillwater Load Uncertainty

Stillwater uncertainty has been considered and discussed in the literature, though primarily for commercial ships. Mansour et al. (1997) suggests the use of a COV of 0.25 for commercial ships and a COV of 0.15 for naval ships. The displacement and draft of a naval combatant stays

relatively constant as compared to ships designed to transport cargo. Based on discussion with Navy experts at NSWCCD, the stillwater bending moment prediction from SHCP is taken to have a bias of unity with a coefficient of variation of 2%.

6.3.3.3 Mission Profile

The mission profile defines the geographic region and duration in which a ship will operate. If a ship is expected to operate primarily in the North Atlantic, a percentage of its life spent in that region must be expressed as in total number of days and during what seasons. This decides the seas the ship is likely to encounter and their associated probability.

The mission profiles and associated sea probabilities define the likelihood of a certain sea state occurring in a specified region at a certain time of year. The sea probabilities used in the US Navy SPECTRA program are Ochi North Atlantic, NATO North Atlantic, General Atlantic, and General Pacific (Michaelson 2000). Lee (1995) developed significant wave height and modal wave period distributions for the North Atlantic, North Pacific, Southern Hemisphere, and coastal areas.

The mission profile used in this analysis consists of a 30-year life spent in the Ochi North Atlantic, with a service life of 3650 days, or one third of the ship lifetime. This is a rather severe mission environment with high probabilities for large waves.

6.3.3.4 Operational Profile

The assumed operational profile must be specified prior to conducting any reliability analyses, and is a primary component in making the resulting safety index of a notional nature. The operational profile defines the operation of the vessel over its lifetime, given a sea state. The use of operation profiles derived directly from historical records, does not adequately account for the uncertainty involved in extrapolating to the actual behavior of all the ships being analyzed. This uncertainty forces the need to promote a sufficiently severe, operational profile for use in design. A new "integrated" combatant operational profile is reported in Michaelson (2000) and is used in the reliability analyses.

6.3.3.5 Sea Spectra

The program SPECTRA allows the user a choice of sea spectrum (Michaelson 2000). The sea spectrum is a mathematical description of the seaway which gives the length and height of waves in a frequency domain. SPECTRA allows the user to choose one of four sea spectra: Pierson-Moskowitz, Ochi 6-Parameter, North Atlantic 2-Parameter or Bretschneider. The Ochi 6-Parameter Spectrum is chosen for use in the reliability analyses.

6.3.3.6 Hull Girder Bending Response to Seaway Loads

The program SPECTRA has been developed to produce the bending moment envelope curves of surface ships given the mission profile, the operational profile, ship characteristics, sea probabilities, response amplitude operators (RAOs), etc. (Sikora 1998b; Michaelson 2000). The Universal RAOs are used to map the seaway environment to a hull girder bending moment. SPECTRA provides the maximum bending moment experienced by the ship hull corresponding to the midship section (station 10). The bending moment varies along the length of the ship sinusoidally, with the maximum at midships, and tapering off to zero at the ends. The bending

moment is increased forward of midships to account for whipping. SPECTRA was used for these predictions with the input parameters as shown in Table 42. The results of the SPECTRA analyses are shown in Table 43, Table 44 and Table 45. Table 43 shows the once-in-a-lifetime loads used for deterministic analyses. Table 44 and Table 45 contain the SPECTRA output required for reliability analyses of the notional destroyer.

Table 42. SPECTRA Input Information for Reliability Analysis

Ship Name	Destroyer
LBP	466 ft
Beam	59 ft
Draft	20.935 ft
Displacement	8672.9 Ltons
Calculation Location	233 ft aft of FP
Stillwater Bending Moment	0 ft-Ltons
Ship Type	Destroyer
Bow Shape	Fine Bow Frigate or Destroyer with Bow Dome
Service Life	3650 days
RAO Source	Universal RAOs
Hull Bending	Vertical Bending
Sea Spectrum	Ochi 6 Parameter
Sea State Probabilities	Ochi North Atlantic
Operational Profile	Integrated Combatant
Average Time Between Slams	Default
Whipping Frequency (Hz)	Default
Whipping Log Decrement	Default
Whipping Initiation Phase Angle	Default

Table 43. Nominal Once-in-a-Lifetime Vertical Bending Moment

Station	Wave Only (ft-Ltons)		Wave + Whipping (ft-Ltons)	
	Hog	Sag	Hog	Sag
5	88080	-88080	90871	-102099
6	115299	-115299	118566	-131693
7	139853	-139853	143625	-158752
8	176161	-176161	180366	-197104
9	176161	-176161	181038	-200614
10	176161	-176161	181742	-204199
11	176161	-176161	181038	-200614
12	159339	-159339	163654	-180959
13	139853	-139853	143625	-158752
14	115299	-115299	118566	-131693
15	88080	-88080	90871	-102099

Table 44. Weibull Distribution for Once-in-a-Lifetime Hog Bending Moment

Station	Slope	Trunc. Value (ft-Ltons)	Scale (ft-Ltons)	Mean (ft-Ltons)	Standard Deviation (ft-Ltons)
5	1.433	86327	7779	7065	5005
6	1.429	112638	10182	9251	6568
7	1.428	136444	12351	11222	7975
8	1.425	171348	15557	14140	10069
9	1.429	171986	15557	14135	10039
10	1.433	172655	15558	14130	10010
11	1.429	171986	15557	14135	10039
12	1.428	155471	14071	12786	9085
13	1.428	136444	12351	11222	7975
14	1.429	112638	10182	9251	6568
15	1.433	86327	7779	7065	5005

Table 45. Weibull Distribution for Once-in-a-Lifetime Sag Bending Moment

Station	Slope	Trunc. Value (ft-Ltons)	Scale (ft-Ltons)	Mean (ft-Ltons)	Standard Deviation (ft-Ltons)
5	1.383	-98015	-7086	-6471	4738
6	1.374	-126425	-9224	-8432	6210
7	1.371	-152402	-11163	-10209	7537
8	1.362	-189220	-13989	-12808	9512
9	1.373	-192589	-14078	-12872	9490
10	1.383	-196031	-14173	-12942	9475
11	1.373	-192589	-14078	-12872	9490
12	1.371	-173720	-12720	-11633	8587
13	1.371	-152402	-11163	-10209	7537
14	1.374	-126425	-9224	-8432	6210
15	1.383	-98015	-7086	-6471	4738

6.3.3.7 Uncertainty of Wave Load Predictions

The uncertainty of the wave load predictions by SPECTRA, B_{WD}, is a combination of the uncertainty in the wave bending moment prediction, M_W, and the uncertainty in the dynamic, wave bending prediction, M_D. First order approximations of the normal distribution parameters for B_{WD} are as follows:

$$B_{WD}\, M_{WD} = B_W\, M_W + B_D\, M_D \tag{6-29}$$

$$B_{WD} = B_W \left(\frac{M_W}{M_{WD}} \right) + B_D \left(\frac{M_D}{M_{WD}} \right) \tag{6-30}$$

$$\overline{B_{WD}} = \overline{B_W} \left(\frac{M_W}{M_{WD}} \right) + \overline{B_D} \left(\frac{M_D}{M_{WD}} \right) \tag{6-31}$$

$$\sigma^2_{B_{WD}} = \left(\frac{M_W}{M_{WD}} \right)^2 \sigma^2_{B_W} + \left(\frac{M_D}{M_{WD}} \right)^2 \sigma^2_{B_D} \tag{6-32}$$

The ratios of M_W and M_{WD} are obtained from SPECTRA for each station. The modeling bias for the wave-only bending moment prediction, B_W, is the ratio of the experimental result to the prediction based on response-amplitude operators. Normal distribution parameters representing the probabilistic characterization of B_W are shown in Table 46, as reported by Sikora et al. (2002).

Table 46. Wave Bending Moment Modeling Bias (B_W) Values

Ship class	Mean	Standard Deviation
Combatants	0.969	0.168
Carriers and LHDs	0.962	0.146

The total bias of dynamic bending (whipping) moment prediction, B_D, is the ratio of the experimental result to the whipping prediction. Sikora et al. (2002) reports the sensitivity of SPECTRA to input variations. The study concluded that the bias between experimental data and the whipping prediction is normally distributed with a mean of 0.9705 and a standard deviation of 0.2465 (COV = 25.4%). The total bias, B_{WD}, normal distribution parameters have been computed as shown in Table 47.

Table 47. Total Wave Bending Prediction Bias, B_{WD}

Station	Hogging Load		Sagging Load	
	Mean	Standard Deviation	Mean	Standard Deviation
5	0.969046	0.163016	0.969206	0.148832
6	0.969041	0.163512	0.969187	0.150253
7	0.969039	0.163716	0.969179	0.150881
8	0.969035	0.164184	0.969159	0.152417
9	0.969040	0.163609	0.969183	0.150551
10	0.969046	0.163017	0.969206	0.148832
11	0.969040	0.163609	0.969183	0.150551
12	0.969040	0.163699	0.969179	0.150831
13	0.969039	0.163716	0.969179	0.150881
14	0.969041	0.163512	0.969187	0.150253
15	0.969046	0.163016	0.969206	0.148832

6.3.4 Hull Girder Reliability Analysis

A Microsoft Excel spreadsheet was developed using the Advanced Second Moment (ASM) reliability analysis methodology as described in Section 2.3.2 for the hull girder ultimate strength limit state discussed in Section 6.3.1 and shown again in Equation 6-33 below.

$$g = B_u\, M_u - B_{SW}\, M_{SW} - B_{WD}\left(Trunc + M_{WD}\right) \tag{6-33}$$

M_u, B_{SW}, B_{WD} and M_{WD} are treated as random variables, while B_u, M_{SW}, and *Trunc* are nonvarying. The ultimate strength (M_u) is assumed normally distributed with the ULTSTR prediction as the mean, and a coefficient of variation of 10%. The ultimate strength modeling bias (B_u) is considered nonrandom and is currently set at one. The stillwater bending moment

from SHCP is considered to be deterministic. The stillwater bending moment bias, B_{SW}, is assumed to be normally distributed with a mean of one and a 2% COV. The wave bending response, M_{WD}, and uncertainty, B_{WD}, are found using SPECTRA, and are treated as discussed in Section 6.3.3.7. Convergence of the ASM algorithm occurred in four iterations.

The ASM algorithm allows the prediction of the *safety index*, β, which represents an approximation to the probability of failure according to the following transformation:

$$p_f = 1 - \Phi(\beta) \tag{6-34}$$

where $\Phi(\beta)$ represents the standard normal cumulative distribution value of β with a mean of zero and a standard deviation of 1.0. Table 48 shows the relationship between the safety index and the probability of failure.

Table 48. Safety Index, β, Conversion to Probability of Failure, p_f

β	p_f
1	0.1587
2	0.02275
3	0.00135
4	3.17E-05
5	2.87E-07
6	9.9E-10
7	1.29E-12

6.3.5 Discussion of Results

The design of station 10, is dominated by the wave-induced, vertical bending moment. This dominance recedes to a much lower level of influence at stations 5 and 15, where shear loading plays a greater role. This will affect the measured reliability along the ship's length if vertical bending is the only load under consideration, as was done in this analysis. As shown in Table 49 and Figure 15, the safety index for the sagging loadcase is seen to range from 4 to 5 at stations near midships. This equates to probabilities of failure on the order of $3\text{x}10^{-5}$ to $3\text{x}10^{-7}$ as seen in Table 48. Hog loading produces a safety index range of approximately 5 to 7. This equates to probabilities of failure on the order of $3\text{x}10^{-7}$ to $2\text{x}10^{-12}$.

The dependability of the hull girder against collapse for the chosen extreme mission may be considered to be the product of the reliabilities along the ships length. This approach assumes independence between stations and is conservative as the upper bound prediction for the probability of failure of a series system. Therefore, the dependability performance measure assessed for the notional Navy destroyer would be $1 - 3.82\text{x}10^{-5}$ for a hog bending moment and $1 - 4.36\text{x}10^{-7}$ for a sag bending moment. This equates to safety indices of 3.96 for hog and 5.07 for sag.

Table 49. Hull Girder Limit State Safety Indices

Station	Safety Index for Hogging Load	Safety Index for Sagging Load
5	10.19	15.48
6	7.35	12.81
7	7.31	8.09
8	4.08	4.92
9	4.55	6.41
10	4.98	7.04
11	4.27	5.85
12	4.54	8.02
13	5.31	6.60
14	6.09	6.41
15	6.62	8.85

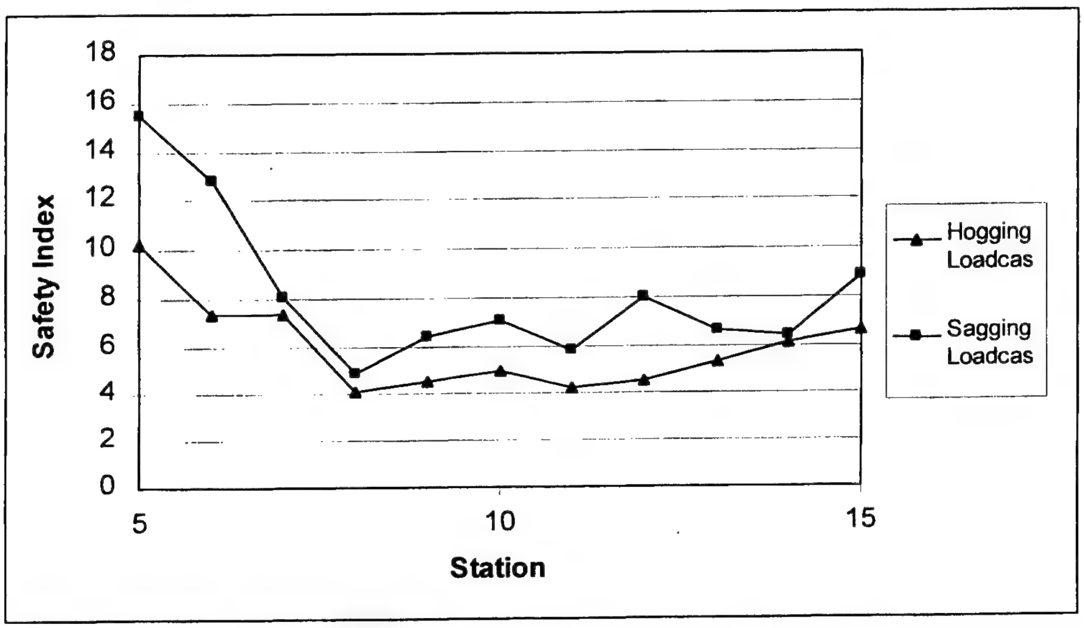

Figure 15. Safety Indices for Hull Girder Collapse of Notional Destroyer

6.4 DURABILITY OF SHIP STRUCTURE

The objective of this case study is to reformulate the conventional cumulative damage, fatigue life prediction methodology in order to produce a more realistic measure of the probability of crack initiation in support of a durability performance metric. Current US Navy methodology is used in the example as discussed in Sikora et al. (1997) and Sieve et al. (2000). The following discussion will demonstrate the conventional fatigue design procedure and a reliability-based procedure that will be used to calculate the probability of failure implied using

available information. The new reliability-based procedure will provide a basis to judge the durability performance of the ship structure and give a probability that the ship structure will not require repair before the end of its life.

For this example, the implied design life of a strength deck detail is assessed using conventional US Navy methodologies. The US Navy fatigue design approach is presented below. The implied design life is considered to be the time-to-failure of the detail assuming a severe mission profile, where first failure occurs at the end of the ship's life. The probability of the time-to-failure for the detail being greater than the developed design life is determined to give a measure of the durability of the ship structure. The sensitivity of the measure is assessed with regard to seaway load uncertainty.

6.4.1 Fatigue Life Prediction

Fatigue lives can be developed using a cumulative damage approach attributed to Miner (1945), which is generally known as "Miner's Rule" and is currently in use by the US Navy (Sikora et al. 1997; and Sieve et al. 2000). This approach hinges on the use of experimental testing to develop a functional relationship between applied, cyclic stress ranges and the number of stress cycles a structural detail will undergo before failing due to crack initiation. The relationship between the stress range, S, and the number of cycles, N, is developed in log-log space and referred to as the S/N curve.

The number of cycles to crack initiation, N, is related to the stress range, S, as follows:

$$N = A \bullet S^{b} \tag{6-35}$$

or

$$\mathrm{Log}(N) = \mathrm{Log}(A) + b \bullet \mathrm{Log}(S) \tag{6-36}$$

where A and b are the intercept and slope, respectively and are found using linear regression analysis on the experimental data in log-log space. Log is the logarithm to a base of 10. Failure is assumed to be crack initiation resulting from fatigue damage. Fatigue behavior of a structural detail tested in a laboratory is assumed to reflect the behavior of a similar detail of interest located within the ship structure. Miner's Rule defines the cumulative damage, D, using Equation 6-37. Fatigue failure due to crack initiation is assumed to occur when $D > 1$. This formulation assumes the detail experiences k stress range blocks, with n_i cycles per i^{th} stress range block.

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} \tag{6-37}$$

For ship structures, the exposure time in a seaway dictates the stress range distribution and the number of load cycles. Longer exposure time equates to higher stresses, and an increase in the number of load cycles. Typically, the critical detail for a ship structure is the one for which the cumulative damage equals unity for the prescribed mission profile and design life. In this situation, the time-to-failure for the detail is the design life of the ship structure. If the cumulative damage is greater than unity, the time-to-failure is considered to be less than the design life, and the ship is more likely to need repair due to fatigue cracking. Ensuring adequate

durability of the ship structure becomes a matter of requiring the cumulative damage prediction for all ship details to be less than 1 ($D < 1$). In conventional design, this is done by using a conservative estimate of the S/N curve to support the assurance of a presumed probability of failure.

The standard error, S_e, of the regression line that defines the S/N curve, is described in Sieve et al. (2000) as "sigma" (σ). Equation 6-38 is used to calculate S_e. The standard error is a measure of data dispersion about the regression line and is comparable to the standard deviation about the mean of a set of data. For k samples, the predicted N (or $\hat{N}$) is compared to the N produced by testing.

$$S_e = \sqrt{\frac{1}{k-2}\sum_{i=1}^{k}\left(\hat{N}_i - N_i\right)^2} \tag{6-38}$$

The standard error is developed in log-log space and is constant along the S/N curve. The coefficient of variation (COV) of the predicted N in normal space is:

$$\mathrm{COV} = 1 - \frac{1}{10^{S_{e(\mathrm{Log\,N})}}} \tag{6-39}$$

The standard deviation of $\hat{N}_i$ is found by multiplying it by the COV calculated above.

The S/N curve developed through a linear regression in Log-Log space is taken as the mean curve. The standard error is used as the standard deviation defining the uncertainty about the mean curve, which is constant with regard to stress range. The population of S/N curves is considered normally distributed about the mean S/N curve. Published, design S/N curves, such as those published by AASHTO (1992), represent the mean S/N curve shifted down by an amount that is twice the standard error developed above. This mean - $2S_e$ curve is reported to assure a probability of failure less than 2.3% (Sieve et al. 2000).

6.4.2 Reliability Formulation

The limit state to be used for the probability of failure calculation is:

$$\mathrm{g} = 1 - \sum_{i=1}^{k}\frac{n_i}{N_i} \tag{6-40}$$

where N_i is developed based on the stress range S_i using the mean, S/N curve. The probability of failure due to crack initiation is:

$$\mathrm{p_f} = \mathrm{P(g < 0)} = \mathrm{P}\left(\sum_{i=1}^{k}\frac{n_i}{N_i} > 1\right) \tag{6-41}$$

In order to develop the probability of failure, reliability techniques can be used as discussed in Section 2.3. For this case study, Monte Carlo simulation is used with Latin-Hypercube sampling to support a Level III reliability analysis. A Microsoft Excel (Microsoft 1999) spreadsheet is used for the analysis in conjunction with @RISK (Palisade Corporation 2000), a risk analysis add-in for Microsoft Excel.

6.4.3 Seaway Cyclic Loading

The seaway loading is developed through the use of the computer codes SPECTRA and SHCP, as discussed in Section 6.3.3. The input information from Section 6.3.3 is used for this case study, and embodies a very severe operational environment leading to potentially excessive conservatism. Instead of only using the maximum bending moment at midships as done for the hull girder collapse reliability analysis, the complete, predicted bending moment distribution is used for fatigue analysis. The bending moment is discretized into 25 stress range blocks as done in Sikora et al. (1997). The bending moment range is converted to a stress range for each discrete block by dividing the bending moment by the section modulus to the strength deck. The bending moment range is the hog bending moment, minus the sag bending moment, after both are adjusted for the stillwater bending moment. Hog bending is considered positive by convention, while sag is negative.

The number of cycles associated with each stress range is developed by SPECTRA and included here as n_i. For the reliability analysis, the probability distribution of n_i is assumed normally distributed with the nominal value taken as the mean. The COV of n_i is treated in the analysis as non-varying, and with COVs of 10, 20 and 40 percent.

6.4.4 Load Cycles to Crack Initiation

The number of cycles to crack initiation, N_i, is predicted using the S/N curve shown in Table 50 (AASHTO 1992) for the Category E structural detail. Conventional fatigue life prediction uses the mean - $2S_e$ curve to assure a fatigue life greater than or equal to the service life with a probability of failure less than 2.3%. The values of S_i and N_i used in the conventional analysis are shown in Table 51.

For the reliability analysis, the mean S/N curve will be used. For a Category E structural detail, the COV of N_i is calculated to be 0.2075 based on a standard error of 0.101. N_i is assumed to be lognormally distributed with the mean defined by the mean S/N curve. The lognormal distribution used is base 10. The values of S_i and N_i used in the reliability analysis are shown in Table 52.

Table 50. AASHTO Category E detail S/N Curve Coefficients (AASHTO 1992)

Category	Mean Minus $2S_e$ Curve		Mean Curve		S_e	Slope, b
	Log(A) for stress range (ksi)	Log(A) for stress amplitude (ksi)	Log(A) for stress range (ksi)	Log(A) for stress amplitude (ksi)		
A	10.401	9.498	10.843	9.940	0.221	-3
B	10.080	9.177	10.374	9.471	0.147	-3
B'	9.791	8.888				-3
C	9.652	8.749	9.778	8.875	0.063	-3
D	9.335	8.432	9.551	8.648	0.108	-3
E	9.030	8.127	9.232	8.329	0.101	-3
E'	8.583	7.680				-3

Note: S can be considered as either stress range or stress amplitude.

Table 51. Fatigue Data for Detail on Strength Deck for a Conventional Fatigue Life Prediction

S_i	n_i	N_i	Log(S_i)	Log(n_i)	Log(N_i)
33.4	1	28792	1.52	0.00	4.46
32.1	2	32543	1.51	0.35	4.51
30.7	5	36975	1.49	0.69	4.57
29.4	11	42249	1.47	1.03	4.63
28.0	22	48577	1.45	1.35	4.69
26.7	44	56234	1.43	1.65	4.75
25.4	87	65589	1.40	1.94	4.82
24.0	166	77138	1.38	2.22	4.89
22.7	315	91566	1.36	2.50	4.96
21.4	593	109831	1.33	2.77	5.04
20.0	1114	133294	1.30	3.05	5.12
18.7	2090	163948	1.27	3.32	5.21
17.4	3915	204763	1.24	3.59	5.31
16.0	7318	260342	1.20	3.86	5.42
14.7	13642	337994	1.17	4.13	5.53
13.4	25279	449878	1.13	4.40	5.65
12.0	46545	617100	1.08	4.67	5.79
10.7	84970	878640	1.03	4.93	5.94
9.3	153572	1311585	0.97	5.19	6.12
8.0	274735	2082738	0.90	5.44	6.32
6.7	487748	3598947	0.82	5.69	6.56
5.3	863658	7029118	0.73	5.94	6.85
4.0	1530882	16662497	0.60	6.18	7.22
2.7	2715655	56235928	0.43	6.43	7.75
0.7	5824980	3598335399	-0.18	6.77	9.56

Table 52. Fatigue Data for Detail on Strength Deck for Reliability Prediction

S_i	n_i	N_i	Log(S_i)	Log(n_i)	Log(N_i)
33.4	1	45842	1.52	0.00	4.66
32.1	2	51814	1.51	0.35	4.71
30.7	5	58871	1.49	0.69	4.77
29.4	11	67270	1.47	1.03	4.83
28.0	22	77344	1.45	1.35	4.89
26.7	44	89536	1.43	1.65	4.95
25.4	87	104431	1.40	1.94	5.02
24.0	166	122821	1.38	2.22	5.09
22.7	315	145793	1.36	2.50	5.16
21.4	593	174875	1.33	2.77	5.24
20.0	1114	212232	1.30	3.05	5.33
18.7	2090	261040	1.27	3.32	5.42
17.4	3915	326026	1.24	3.59	5.51
16.0	7318	414519	1.20	3.86	5.62
14.7	13642	538157	1.17	4.13	5.73
13.4	25279	716299	1.13	4.40	5.86
12.0	46545	982553	1.08	4.67	5.99
10.7	84970	1398978	1.03	4.93	6.15
9.3	153572	2088318	0.97	5.19	6.32
8.0	274735	3316154	0.90	5.44	6.52
6.7	487748	5730274	0.82	5.69	6.76
5.3	863658	11191823	0.73	5.94	7.05
4.0	1530882	26530173	0.60	6.18	7.42
2.7	2715655	89539335	0.43	6.43	7.95
0.7	5824980	5729301025	-0.18	6.77	9.76

6.4.5 Analysis

The conventional analysis predicts the time to crack initiation to be 795 days for the severe mission profile and using the mean - $2S_e$ S/N curve. This is predicted by varying the design life and resulting seaway loading until the cumulative damage, D, approximates unity. If the mean, S/N curve is used, the time-to-failure for the detail is found to be 1300 days.

@RISK 4.0 was used to conduct a Monte Carlo simulation, reliability analysis of the limit state function defined in the Microsoft Excel spreadsheet to determine the percentage of times that $g > 0$. The Latin-Hypercube sampling option is used with 10,000 cycles in the simulation with a random number generator seed value of 1.0. The probability of fatigue failure for an operational, service life of 795 days is shown in Table 53 for varying levels of uncertainty on n_i. Assuming the uncertainty of 20% for n_i, the durability of the structural detail is shown to be 99.95%. The durability of the detail, assuming an increased service life of 1300 days, is found to decrease to 32.99%

Table 53. Probabilities of Failure and Reliabilities for Critical Detail Fatigue Failure

COV of n_i	Reliability	Probability of Failure
0	99.972%	0.028%
10%	99.970%	0.030%
20%	99.950%	0.050%
40%	99.750%	0.250%

6.4.6 Conclusions

The objective of this case study is to reformulate the conventional cumulative damage, fatigue life prediction methodology in order to produce a more useable measure of the probability of crack initiation in support of a durability performance metric. The conventional US Navy fatigue design procedure and a reliability-based procedure are presented for a critical detail on the notional destroyer. The new reliability-based procedure provides a basis to judge the durability performance of the ship structure. For this analysis, the durability performance of the critical detail is 99.95%, for the ship structure associated with an extreme mission profile of 795 days.

More formal treatment of the uncertainty of n_i is required to obtain a more viable answer. Current load uncertainty models concentrate on stress uncertainty, not the uncertainty in the number of cycles. Though the analysis is relatively insensitive to the variation of n_i, the uncertainty in n_i has not been addressed adequately. Current load uncertainty models concentrate on stress uncertainty, not the uncertainty in the number of cycles. If a functional relationship can be established between n and S (i.e., a curve fit), the limit state can be reformulated to be:

$$p_f = P\left(\int_{S_1}^{S_2} \frac{n(S)}{N(S)} dS > 1\right) \tag{6-42}$$

The new formulation would allow the uncertainty in S to be propagated through to n and N.

For this example, the implied design life of a strength deck detail is assessed using conventional US Navy methodologies. The implied design life is considered to be the time-to-failure of the detail assuming a severe mission profile, where first failure occurs at the end of the ship's life. The probability of fatigue failure occurring before the end of the developed design life is determined to give a measure of the durability of the ship structure. The sensitivity of the measure is assessed with regard to seaway load uncertainty. This case study demonstrates that it is possible to calculate the probability of fatigue damage for a ship detail, given current fatigue data and methodologies

6.5 CASE STUDIES SUMMARY

The case studies presented in Sections 6.1 to 6.4 demonstrate the use and implications of the different performance metrics and their supporting reliability analysis methodologies. The notional destroyer shown in Figure 9 is the basis for the case studies. The hull is of conventional design and construction for a US Navy combatant, using longitudinally stiffened plating with transverse framing. The deckhouse is built from fiber reinforced plastic (FRP) skin, balsa core, sandwich panels.

The first case study considers the top-level requirement (TLR) for the deckhouse to be capable of withstanding a lateral pressure load with some prescribed probability of survival. The use of FRP structures requires the inclusion of detailed fabrication information in the development of basic strength variables for the design. The variation of material properties is much greater than with metallic structures due to the material being manufactured in conjunction with the structural component on-site by each fabricator. Test specimen batches from a sample of fabricators are analyzed to determine the impact of fabricator choice on the resulting capability performance of the topside structure. It is shown that the choice of fabricator can significantly affect the range of acceptable design options. Use of the fabricator of Batch 2 provides the greatest range of acceptable designs at both the 90 and 99 percent reliability levels. The conditionality of the composite panel reliability prediction must be taken into account when considering the acceptability of the 90 or 99 percent requirements. The probability of the structure failing is conditioned on the definite occurrence of the design load. For the design of the structure against this failure mode in support of the capability metric, the likelihood of the load occurring is taken as unity. The actual probability of the load occurring is less than one, which would increase the reliability of the panel above the 90 or 99 percent values presented.

The second case study demonstrates currently available methodologies for designing unstiffened plating against excessive permanent set, and the traditional limitations used to judge when failure has occurred. A procedure is demonstrated for addressing vague failure definitions using subjective probabilities, as discussed in Chapter 4, to capture historically accepted permanent set limitations. The traditional failure definitions lead to a significant probability of failure for the plate used in the example, with values ranging from 15.9 to 30.4 percent. The sensitivity of the probability of failure is shown to be highly dependent upon the chosen response model and failure threshold. To effectively support a capability measure, the methods presented in this case study will require greater emphasis to be placed on the predictive models, failure

thresholds and supporting information in order to validate the usability of the results for decision-making.

The third case study addresses the dependability performance associated with hull girder collapse failure during a specified mission. The environmental load information is provided for the notional ship design for an extreme mission profile. The safety index for the sagging load case is seen to range from 4 to 5 in the area of interest for the chosen failure mode and loading at stations near midships. This equates to probabilities of failure on the order of $3x10^{-5}$ to $3x10^{-7}$. Hog loading produces a safety index range of approximately 5 to 7. This equates to probabilities of failure on the order of $3x10^{-7}$ to $2x10^{-12}$. The dependability of the midship section for the chosen extreme mission may be considered to be the product of the reliabilities found for the specified failure mode along the ships length. This approach assumes independence between stations and is conservative as the upper bound prediction for the probability of failure of a series system. Therefore, the dependability performance measure assessed for the notional Navy destroyer would be $1 - 3.81839x10^{-5}$ for a hog bending moment and $1- 4.35987x10^{-7}$ for a sag bending moment. This equates to safety indices of 3.96 for hog and 5.07 for sag.

The objective of the fourth case study, discussed in Section 6.4, is to reformulate the conventional cumulative damage, fatigue life prediction methodology in order to produce a more useable measure of the probability of crack initiation in support of a durability performance metric. The conventional US Navy fatigue design procedure and a reliability-based procedure are presented for a critical detail on the notional destroyer. The prediction of durability performance of the notional combatant using a reliability-based, fatigue analysis methodology is conducted using extensions of existing technologies, revised to allow prediction of the probability of crack initiation during the design life of the notional combatant. The new reliability-based procedure provides a basis to judge the durability performance of the ship structure and give a probability that the ship structure will not require repair. For the detail on the example Navy destroyer, the durability performance is found to be 99.95% for the previously stated conditions.

Comparison of the results of the case studies provides the basis for determining their significance with regard to the importance of the particular failure modes. Table 54 shows a summary of the case study results, and provides an approximate ranking of the failure consequence where 1 is the most severe and 4 is the least. The most probable failure is that of excessive permanent set, which may not impinge the performance of the structure in any significant manner but could degrade other non-structural system performance. The next most probable failure mode is that of topside, composite panel rupture due to a dynamic, lateral pressure load with failure probabilities of 1 or 10 percent. As the probability calculation is conditional on the load, the actual probability of failure is much less than the reported values, ultimately making this failure mode much less likely. The criticality of the topside panel failure is less serious than hull girder collapse, but more serious than excessive permanent set or crack initiation. The probability of crack initiation is shown to be 0.05% over a prescribed life of 795 days in a severe environment. The consequences of a crack are negligible unless the crack grows beyond the critical crack length, and becomes unstable, leading to fracture of larger structural components. The probability of hull girder collapse is the lowest of the four, which is appropriate as it is the most critical failure mode with catastrophic consequences.

Table 54. Risk Evaluation for Case Study Failure Modes

Performance Metric	Failure Mode	Performance Measure	Probability of Failure	Consequence Ranking
Co'	Topside, panel rupture under dynamic pressure load	99 %	<<0.01	2
Co'	Excessive panel deformation due to wave loads	75.3 %	0.247	4
Do'	Hull girder collapse due to wave loads	99.996 %	$3x10^{-5}$	1
Ao'	Fatigue crack initiation due to cyclic wave loads	99.95 %	0.0005	3

The calculated performance metrics can be used to determine the acceptability of the structural design by a ship manager. The failure modes addressed in the case studies reflect a sample of the range of failure modes affecting ship structural performance. The capability of ship sub-structures is described by the first two case studies. The capability of the topside structure against an air-blast is more significant than the capability of the hull, shell plating against permanent set. The much higher likelihood of excessive permanent set does make it an issue needing resolution if the damage threshold is appropriate to the design needs. The dependability of the structure is measured as the probability the hull girder will survive an extreme mission. The durability of the structure is measured as the probability that a critical detail on the deck will not fail over a prescribed period of time.

The overarching performance requirements of the ship structure (TLRs) could be a measured structural durability not less than 99 %, a measured dependability not less than 99.999% and a measured capability not less than 99 %. The notional ship design used in the case studies would be deemed acceptable, except in the case of unstiffened panel, permanent deformation. The design manager can have his technical experts consider the basis for the unstiffened plate capability performance analysis and consider whether the risk of the panel not meeting the requirement for this performance TLR is excessive. If so, the design would be rejected.

Treatment of the failure modes in a performance-based environment requires that the consequences of failure be mapped into the performance metric domain of choice. The top-level

requirements for each performance metric can be developed through risk assessment of the total system.

Uncertainty in the performance measures has not been addressed in the case studies. The uncertainty of the performance measure stems from ambiguity and vagueness in the analysis process. As discussed previously in Section 3.2, each performance measure is notional in nature and must be treated as such.

Combination of the performance measures into one measure of system effectiveness is not recommended due to dependencies between the proposed performance metrics. As discussed in Section 2.4, OPNAVINST 3000.12 (OPNAV 1987) proposes defining the System Effectiveness (SE) as SE = Co x Do x Ao. The Draft version of OPNAVINST 3000.12a (OPNAV 2001) does not include this approach.

The platform managers use the metrics associated with electrical and mechanical systems to address a range of customer needs. Ao helps determine the logistical pyramid in support of the system. Co helps determine the effectiveness of the system in operational simulations. Do allows the manager to make strategic decisions as to how many systems are required for a particular mission, and ensure adequate coverage.

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS

This report identifies and demonstrates, reliability-based operational performance metrics as they apply to surface ship structures, specifically, those of the US Navy. A method is presented for developing three performance metrics: structural operational capability, structural operational dependability and structural operational durability. Special emphasis is placed on defining the failure modes and definitions. Case studies are based on a notional US Navy ship design and include topside composite structures under a dynamic lateral pressure, unstiffened plate deformation due to wave slap, hull girder collapse in an extreme seaway and the initiation of a fatigue crack in a critical structural detail on the strength deck.

7.1 CONCLUSIONS

The following conclusions can be drawn from this report:

1. This report demonstrates that ship structural operational performance can be quantitatively assessed using reliability-based performance metrics. Ship acquisition managers can use the resulting measures of performance to determine structural design acceptability with regard to planned platform operation.
2. Structural reliability theory is shown to be applicable for the measurement of the operational performance of platform structural systems in terms similar to those used for other platform systems, such as electrical and mechanical systems. Operational performance of non-structural platform systems is discussed in OPNAVINST 3000.12 (OPNAV 1987) and is transformed in this report to apply to ship structural systems.
3. The structural operational *durability* performance measure is shown to provide the probability that the platform structure will not require repair over a prescribed lifetime. This provides the likelihood that the ship structure will be ready for a mission when called upon and is a contributing factor to the structural operational availability. Existing structural fatigue prediction tools and information are modified to support a durability measure through application of structural reliability analysis methods.
4. The structural operational *dependability* performance measure is shown to provide the probability that the ship structure will "be there" throughout an extreme mission, once the mission begins. This measure provides a quantitative level of assurance that once the mission has started, the structure will successfully resist the seaway loads.
5. The structural operational *capability* performance measure is defined as the ability of the structure to support operational needs such as those associated with resisting combat, operational or accidental loading, as opposed to seaway loading. This measure provides a probability that the structure will successfully support the function of dependent systems and other operational needs.
6. Ambiguity and vagueness (e.g., modeling uncertainties, basic variable uncertainties and lack of knowledge) cause uncertainty in the performance prediction. The uncertainty in the performance prediction supports the treatment of the prediction as notional. A mapping of the notional prediction to top-level requirements for structural performance of new ship designs can be developed using a calibration to historical levels of performance found in previous ship structures. Calibration is the use of a benchmark such as an acceptable ship structural design to assess the accuracy of a new prediction

tool or methodology. If the new tool measures the same or better performance in a new design as compared to an older, acceptable structure, then the new design can be considered to be acceptable as well.

7. Using reliability analysis, failure can be defined as crisp or vague. Crisp failure is often associated with *ultimate* limit states. An ultimate limit state defines a structural response failure threshold associated with behavior such as collapse or rupture. Vague failure is often associated with *serviceability* limit states. A serviceability limit state defines a structural response failure threshold associated with behavior such as excessive deflection, vibration or stiffness. Both types of failure are described to support measurement of operational performance.

8. As an alternative to *possibilistic* approaches, *probabilistic* methods can be used to effectively articulate vague failure thresholds in the context of a reliability analysis. Probabilistic approaches can also be used to quantitatively update historic failure thresholds.

7.2 RECOMMENDATIONS

Application of the reliability-based, performance management methodologies presented in this report will require dedicated research to validate the techniques and gather the necessary supporting information for formal use in the acquisition process. The following recommendations are provided:

1. As shown in the case study of Section 6.2 which considers the capability of an unstiffened plate to resist excessive permanent set, the choice of a structural response model and failure definition can significantly impact the measured reliability and influence the assessed performance of a structure. Clear, consistent failure definitions must be associated with each potential failure mode and response model in order to minimize the uncertainty in the measured performance.

2. The uncertainty in reliability-based performance measures will require the predicted notional assessments to be mapped to the actual performance needs of the ship managers and operators. Establishing this mapping will require calibration of the new technologies to known examples of acceptable performance and close attention to the modeling and basic variable uncertainties of the underlying predictions.

3. True measurement of the operational availability will require a validated model of the ship structural maintenance strategy developed using reliability, or probabilistic, models. As these models do not currently exist, the structural operational durability measure is presented in this report.

4. The measurement of the structural durability requires the development of a suitable operational scenario. The case study discussed in Section 6.4 uses an extreme mission profile of 795 days of operation in the North Atlantic to determine the durability of the structure. This operational scenario supports a cumulative damage prediction of unity for the structural detail using conventional fatigue life prediction techniques, but does not reflect a realistic operational expectation for the ship over its lifetime.

5. Corrosion and fatigue cracking models must be included to account for the time-based degradation effects on capability and dependability. Time-varying reliability models

are reported in the literature, but have not been incorporated into the work presented in this report, nor has the US Navy embraced them in reliability-based guideline development.

6. Changes to traditional ship structural designs require changes in the methods used to design such structures. Acceptance of new methods will require a deliberate effort by the decision-making and technical communities in order to realize any benefit.

7. Aggregation of the reliability-based performance predictions associated with a wide range of failure modes for a particular performance metric requires application of a system reliability model. The approach presented in this report is conservative. It treats the structure as a series system where the reliability is the product of individual failure mode reliabilities. This supports the view that the first failure mode occurrence coincides with the onset of unacceptable structural performance. As each failure mode per performance measure can have a differing consequence, risk-based approaches should be applied for aggregation of probabilities for each failure mode to ensure this assumption is not overly conservative, or misleading, in the context of performance.

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